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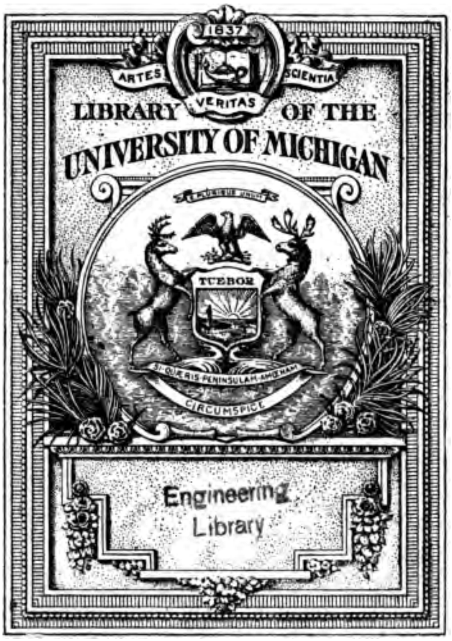
LECTURES
ON
COMPASS ADJUSTMENT

CAPTAIN W. R. MARTIN, R.N.



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LECTURES

ON

COMPASS ADJUSTMENT

(FORMERLY GIVEN TO THE NAVIGATING OFFICERS
OF THE ROYAL NAVY),

BY

CAPTAIN W. R. MARTIN, R.N. (RETIRED),

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PREFACE.

THE following Lectures formed a part of the course of instruction I gave for many years at the Royal Naval College, Greenwich, to audiences composed partly of senior officers, but principally of the Navigating Officers of the Fleet.

The lectures were profusely illustrated by diagrams (a selection of which are given in this book), and followed by practical work, originally in a small vessel kept for that purpose in the basin of the Royal Naval Victualling Yard, Deptford, and later on, by means of a large iron model, progress being further tested by Examination Papers principally set by the Superintendent of Compasses, from which a selection is given at the end of each chapter of this book.

My classes were, of course, familiar with the use of the compass, and more or less acquainted with the official Text-book on the subject of Adjustment, to which I make frequent reference. The main objects kept in view in this course of instruction were to familiarise executive officers with the mechanical operations involved, and to explain the theory without appealing much to mathematical knowledge. In 1903 the work was transferred to H.M.S. *Mercury* at Portsmouth, with the great advantage of affording the means of instruction in a sea-going ship.

For permission to copy the Charts at the end of this book from the "Manual of Deviations," I am indebted to the courtesy of the Lords Commissioners of the Admiralty.

W. R. MARTIN,
March, 1906.

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CONTENTS.

LECTURE I.

General Remarks—Construction of Compass—Thomson's Card—Measurement of Power of Magnets—Swinging Ship—Bearing Plate or Dumb Card.

LECTURE II.

Hard Iron, Properties and Effects of—Liverpool Compass Committee—Semi-Circular Deviation—Effect of Change of Position—Correction of Deviation caused by Hard Iron—Sub-Permanent Magnetism.

LECTURE III.

Vertical Soft Iron, Properties and Effects of—Semi-Circular Curve from Same—Soft Iron Rods—Effect of Change of Position—Flinders' Bar—Separation of Parts of Semi-Circular Deviation—Correction.

LECTURE IV.

Quadrantal Error—Symmetrical Horizontal Soft Iron—Quadrantal Curves—Octantal and Sextantal Errors—Correction by Spheres—Unsymmetrical Soft Iron—Second Part of Quadrantal Error—Correction.

LECTURE V.

The Co-efficients—Analysis of Deviation Table – Illustrations of Co-efficients—Curves caused by Co-efficients.

LECTURE VI.

Directive Force or Pointing Power of a Compass—Causes affecting same—Mode of Measurement—Deflector—Construction and Uses of same.

LECTURE VII.

Heeling Error—Various Causes of same—Effect of Change of Position—Various Measurements of Vertical Force—Correction in Harbour and at Sea.

LECTURE VIII.

Resumé of Preceding Lectures —Adjustment of a New Ship by Bearings and by Deflector.

INDEX.

PAGE
ADMIRALTY COMPASS 3
Manual 2
Amplitude 9
Attraction of Land 8, 84
BEALL'S DEVIASCOPE 64
Bearing, Error in 23
——— Magnetic—How Found ... 10
——— Plate 11
CO-EFFICIENT (A) 23, 55
——— (B) 22. 57
——— (C) 22, 57
——— (D) 43, 57
——— (E) 47, 58
——— Heeling 79
Co-efficients 52
——— Approximate 54
——— Approximate and Exact
Connection between 61
——— Curves of 62
——— Exact 54
——— How Found 55
Compass, Admiralty 3
——— Committee 2, 16
——— Single Needle 2
——— Thomson 3
Correction by Deflector 74
——— for Hard Iron 21
——— for Heeling Error 84
——— for Quadrantal ... 45, 47
——— for Vertical Soft Iron ... 35
——— of all Errors 92
——— with One Magnet 23
Correctors, Quadrantal 46
Curve, Combined 38, 47, 61
——— from Hard Iron 17
——— from Horizontal Soft Iron... 41
——— from Vertical Soft Iron ... 29
——— Quadrantal 41, 48, 49
——— Semi-circular ... 17, 29, 38
Curves of Co-efficients 62
DEFLECTOR 73
——— Correction by 74
Deviascope, Beall's 64
Deviation from Hard Iron 17
——— Semi-circular ... 17, 35
——— Semi-circular—Separation
of Parts 35
——— from Vertical Soft Iron ... 29
——— Quadrantal 42
Dip 19, 32
Directive Force 64
EQUATION, APPROXIMATE 54
——— Exact 53
——— Fundamental 53
Error, Gaussin 8
——— Heeling 78
——— Total 9
Errors, Causes of 1
FLINDER'S BAR 34
Force, Directive 64
——— Horizontal 19, 32
——— Total 19
——— Vertical 19. 32
Forces, Horizontal, Compared 71. 72
GAUSSIN ERROR 8
Galvanometers 7
HARD IRON DEFINED 12
——— Correctors for 20
Heeling Co-efficient 79
——— Error 78
Heeling Error, Causes of 81
——— Changes in 82
strument 88
Horizontal Force 19, 32
by Deflection 72
——— by Vibrations 72
INDUCTION 27
Iron, Hard 12
——— Soft 27
LAMBDA (λ) 67
——— and D, Connection between 68
Land, Attraction of 8, 84
Latitude, Effect of Change of ... 19
Liverpool Committee 16
MAGNETIC BEARING—HOW FOUND 10
Magnets, Action of 6
Manual, Admiralty 2
Mu or Vertical Force 87
Multiplier 89
NEEDLE, HORIZONTAL 70
Needles 2
OCTANTAL ERROR 43
PELORUS 11
Pointing Power of Compass ... 65
Points, Quadrantal 43
Position, Effect of Change of 19, 32
QUADRANTAL ERROR, SYMMETRICAL 40
——— Total 48
——— Unsymmetrical 47
——— Correction of 44
Quadrantal Points 43
RETENTIVE MAGNETISM 26
Rod (*a*) 40
——— (*b*) 48
——— (*c*) 29
——— (*d*) 48
——— (*e*) 42
——— (*f*) 57
——— (*g*) 90
——— (*k*) 29
Rods, Soft Iron 29
SEMI-CIRCULAR DEVIATION 17, 35
——— Correction of ... 21, 22, 36
——— Separation of Parts... ... 35
——— Total 38
Sextantal Error 43
Soft Iron Defined 27
——— Horizontal Symmetrical ... 40
——— Unsymmetrical 47
Spheres, Action of 50
Sub-permanent Magnetism ... 24
Swinging Ship 8
THOMSON COMPASS 3
Total Force 19
VERTICAL FORCE 19, 32
Instrument 88
Vertical Soft Iron 27
Vibrations 87
Vibrations, Vertical... 87
——— Horizontal 70

LECTURE I.

Preliminary Remarks—Construction of Compass—General Observations on Swinging Ship—Action of Magnets—Bearing Plate or Pelorus.

Although it may rarely fall to the lot of any navigator in times of peace to be called upon to adjust the compass of a new ship (a work usually, both in the Royal and Mercantile Navies, performed by experts), it is a modern sailor's duty to understand how to periodically correct the smaller compass errors which invariably appear with lapse of time, and, moreover, a knowledge of the original magnetic condition of a ship and the principles on which the corrections are first made, materially assist in understanding the subsequent action of the compass in the actual practice of navigation.

The large and peculiar errors commonly found to exist in uncorrected iron ships (especially in vessels of war) are due to the magnetic actions of the various kinds of iron and steel used in their construction: actions which manifest themselves in two inseparably connected ways, viz.—(1) By causing large deviations, occasionally evidenced by the ship's attraction on some points completely overpowering that of the earth, and (2) By causing the directive force or pointing power of the compass to be greatly augmented or diminished when the ship's head is in certain directions.

Both of these effects have to be considered, for though the arithmetical application of a deviation of 30° to a compass course is no more difficult than that of 3°, yet in the former case, on one of the courses eight points from where the greatest deviation is observed, the compass will be found to have almost lost its pointing power.

The reason for this will be shown later on, but accepting it at present for a fact, we shall see that a compass might be corrected by (1) either the more ordinary way of eliminating the deviation, or (2) by equalising on all points the directive force; when either of these operations is mechanically performed the other result necessarily follows.

The chief object, however, is the latter, since, not only is the deviation removed, but greater steadiness of the card is attained as the ship rolls and pitches.

Both of these methods of correction are in practical use, and it may make matters more clear if, from the outset, we realise that in either way of going to work, what is really being corrected is the disturbing action of the *ship*, and that a compass in an ordinary iron vessel—however great its original error—when relieved by suitable correctors from the various magnetic pulls of the ship, will be as free from deviation and generally act almost as well as if on shore or in a wooden ship.

The great object sought in correcting a compass is therefore to obtain one which shall under all possible circumstances remain perfectly steady, but it must be remembered that even after accurate compensation for all errors due to the ship, and after the weight of the card has been brought to a minimum so as to reduce friction, yet the extremely irregular movement in space of the pivot, acting on even the small surface of the cap necessarily resting on it, will by itself cause *some* motion in the compass as the ship rolls and pitches.

The nature and methods of applying correctors to compasses have for many years been subjects of both theoretical and practical study in the Compass Department of the Admiralty, with the very satisfactory result that, if accompanied by intelligent co-operation on the part of the navigator in any sea-going vessel, the original very large errors, both when the ship is upright and heeled over, can always be reduced to, at most, very small amounts. It is the object of these Lectures to stimulate such intelligent co-operation by explaining in simple language the nature of the various operations performed by the adjuster to remove these errors, referring the more mathematical reader to the Admiralty Manual for the Deviations of the Compass (referred to in future as the " Manual "). In this preliminary lecture we will first briefly look at the chief points considered in the construction of a good compass.

The original and most simple idea of such an instrument was embodied in that of a compass directed by a *single* magnet (commonly called a " needle "), and for many years this was the form it assumed; originally, the needle was free from the card, but afterwards more conveniently attached to it.

Single-needle cards, as they are called, are, however, always unsteady, moving with every slight movement of the ship and "wobbling" a great deal; moreover, they are altogether unsuited to correction in iron ships for other important reasons. Such compasses imperfectly answered the rough purposes of navigation in days gone by, but after several men-of-war had been wrecked through their unsatisfactory performances, the Admiralty, in 1820, requested Professor Barlow, an eminent authority on magnetism, to report on the condition of the compasses of the Royal Navy.

This report having very strongly condemned the existing type, stating that of those in store " at least one-half were mere lumber," an influential Committee was appointed in 1838, whose most thoroughly practical and theoretical experiments resulted in the introduction into the Royal Navy of the formerly well-known Admiralty Standard Compass, for many years a most reliable and excellent instrument which answered all purposes during the existence of wooden or composite ships, and is still supplied to vessels of war for shore observations.

The leading feature of this compass is the arrangement of four long powerful needles under the card, so placed that at its centre the angle N O N subtended by the similar poles of each pair is 30° (Fig. 1), an arrangement which theoretically and practically gives in wooden ships great steadiness and strong pointing power. A modification of this, where only two long needles were employed, was for many years used in the Mercantile Marine, and, at a later date, as a steering compass in the Royal Navy; in this case, the angle N O N at the centre subtended by the similar poles was 60° (Fig 2).

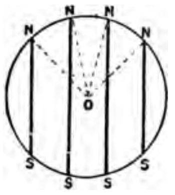


Fig. 1.

On the introduction of iron ships it was both theoretically and practically found that by either of these arrangements the errors caused by the length of the needles was very greatly decreased.

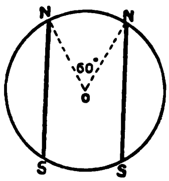


Fig. 2.

In later years the vibration produced by increased speed rendered such heavy cards unsatisfactory, and the introduction of iron as the material for ship building soon showed that long powerful needles, even arranged as above, were badly adapted for several parts of compass adjustment, the necessity for which soon arose from the enormously increased deviations as compared with those in wooden or composite ships.

A system of partial correction was therefore adopted for some years, but in the Royal Navy the great increase of thickness in armour soon necessitated certain special corrections to which these compasses did not at all lend themselves, and led to falling back in their construction on more practical applications of fundamental magnetic laws which have been happily embodied in the modern short needle cards, of which that originally patented by Lord Kelvin in 1877, and now almost universally used, may be taken as a type (Fig. 3).

The leading features of this excellent compass (known as the Thomson compass) are as follows:—(1) reduction of weight to a minimum, (2) short light symmetrically arranged needles, (3) mode of suspension of needles, (4) slow period of swing.

(1). The first point is attained by using short light needles, and by taking away the unnecessary central part of the card, strengthening it round the margin with a rim of aluminium (the lightest known metal) and by radial silk threads which also tend to take up the vibrations caused by the screw; the slight friction in the working of this very light card being further reduced by making the pivot of iridium and the cap of sapphire (two of the hardest substances known); the actual weight of each card is written on the underside, and for the 10-inch card adopted in the Navy for a standard compass is approximately 180 grains, that of the former Admiralty standard pattern being 1525 grains.

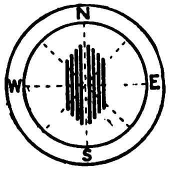


Fig. 3.

(2). The importance of the second point will be realised when we consider that the practical rules on which a compass adjuster works are based on the theory that the length of the compass needle is nothing, for directly we have to consider the action of the ship or of the correctors employed on *both* poles of the compass, the theory and practice of compensation become very complicated and unpractical.

Hence one principal advantage of short needle compasses and the importance of placing them as far as possible from individual masses of iron; strange as it may seem, the theoretical idea of a compass which is only a magnetic *particle*, is most nearly obtained by using a number of short needles (eight in the compass we are considering) and arranging them on the same *principle* as on the old Admiralty compass.

In Thomson's 10-inch card the length of the longest needle is $3\frac{1}{4}$ inches, while in the former Admiralty standard pattern it was 7·3 inches.

(3). The third point is attained by keeping the needles (and centre of gravity of the whole card) well below the point of suspension, thus rendering the compass more steady and without any counterpoise, keeping the needles practically horizontal in all magnetic dips, a result in the older-fashioned cards attained by a sliding weight.

(4). The marked superiority of the Thomson card over others chiefly depends, however, upon the fourth point, which is the practical application of the principle that great steadiness of the compass, when rolling, can be attained by making its period of swing very much slower than the period of roll of the ship.

The period of oscillation or swing of a compass may be reduced by either increasing its moment of inertia or by decreasing its magnetic moment, which in a magnet is the product of the amount of magnetism imparted to one of its poles, multiplied by the distance between these poles.

The inertia of a compass can be increased by making it heavier, but this also makes it more sluggish owing to increased friction on the pivot, so that the desired result is best attained by the second method, which is that of using short weak needles; by these means the period of swing (to *and* fro) of the 10-inch card is made about 40 seconds in England—a period far slower than that of the roll of any ordinary ship.

Removing the central part of the card and thus throwing such weight as remains away from the point of suspension tends to the same end.

The small amount of magnetism given to these short needles, of course, diminishes their directive force, but in the compass we are considering its whole weight is intentionally reduced to a minimum, so that only small directive force is needed to make it act.

The actual period of swing (P) of each completed Thomson card is written on the underside.

Minor points connected with Thomson's compass which may be noted are these:—

(1) The bowl is made of brass, and, indeed, any non-magnetic material would answer the purpose; it is weighted underneath, so as to keep it steady, by an expansion chamber partly filled with castor oil.

Formerly, when long powerful needles were used, it was very important to make the bowl of copper, and of such dimensions that the poles of the needles worked very close to the bowl, for as the compass swung one way it induced a magnetic current in the copper in the opposite direction and thus, without weakening directive force, the compass was brought rapidly to rest.

This valuable effect (developed most strongly in silver) is not applicable or requisite with short weakly-magnetised needles.

(2) It is useful to remember that in changing a Thomson card for one of different weight or period, exactly the same deviations will exist, which is practically true for compasses of even very different patterns, weights and lengths of needles, provided that such needles remain in exactly the same horizontal planes, and that they are sufficiently far from disturbing iron that their lengths may be disregarded, or in other words, the compass may be regarded as a magnetic particle.

(3) The application of large masses of soft iron (in the form of hollow spheres) to correct quadrantal deviation, necessitated abandoning the old way of taking bearings by direct observation, and substituting for it, in most cases, the total internal downward reflexion, in a glass prism, of the object whose bearing is required, the observer looking directly on the card. When, however, the object is faint or low down, provision is made by reversing the

prism to look directly at the object and reflect the image of the card up to it.

(4) Binnacles are provided with two sets of numbered fore and aft holes for corrector magnets, and only one set of athwartships holes; the object of this is to enable the fore and aft magnets to be kept lower down than would be otherwise possible, and thus obviate any tendency they might have to induce magnetism in the heel of the Flinders bar *(see page 37)*.

The vertical distances between the holes are regulated so that practically each successive step up or down with the same magnet will produce an equal effect on the compass.

The amount of magnetism imparted to either pole of a compass needle is measured by the repulsive effect it has on another and equal magnetic pole placed at a certain distance from it, and both theory and experiment show that the effect of a *single* magnetic pole on a compass having short needles varies inversely as the square of the distance from it; thus, if at a distance of 6 feet in a certain direction from the centre of the compass such a pole causes 2° of error, at half the distance, or that of 3 feet measured in the same direction, it will cause *four* times this error, or 8°

The effect of a *magnet* on such a compass depends upon (1) the amount of magnetism impacted to its poles; (2) the length of the magnet, or rather the distance between its poles; and (3) the distance the middle point of such magnet is from the centre of the compass, such distance being sufficiently great for us to be able to consider the attractive ond repulsive effects on *each* end of the compass needle to be acting parallel to each other, so that if the original error of 2° be occasioned by *both* poles of a magnet, on reducing the distance as before to 3 feet, 16° of error will be observed, the effect now varying inversely as the cube of the distance.

If we place a magnet, AB (Fig. 4 *a*), on deck, before or abaft a compass having short needles, with its centre, O, on the fore and aft line, and its length at right angle to that line or pointing athwartships—in this position it is said to be be "broadside on"—and if at a distance, OK, of, say five feet (measured from centre of compass to middle of magnet), and pointing East and West, it causes 6° of deviation, it will be found, if moved parallel to itself, to produce the same error at the same distance, or in any position on a vertical circle, having its centre at that of the compass and its

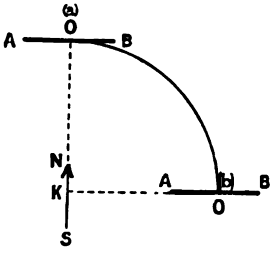


Fig. 4.

radius 5 feet, acting exactly as a weaker magnet will do similarly pointed, but passing through the centre of the compass.

The same magnet, (Fig. 4 *b*), if placed athwartships in the plane of the needles on either side of the compass, and pointed to its centre in an East and West line at the same distance, measured in the same way as before, will be found to produce 12° of error; in this position a magnet is said to be "end on."

Thus a magnet always acts in a direction parallel to its own length, and is twice as powerful when placed end on as when broadside on.

In other words, the effect of a small magnet whose length is l on a magnetic particle, at a distance r from its middle point, is $\frac{2l}{r^3}$ if applied end on, and $\frac{l}{r^3}$ if presented broadside on; this supposes that r is not less five times l, and that the length of the magnet is less than fifty times its breadth.

A magnet, whether broadside or end on, acts most powerfully on a compass when its length lies in a direction at right angles to the north and south line of the disturbed compass, when the force with which it is acting is measured (in terms of the earth's horizontal force) by the natural sine of the error it produces. Thus, if a magnet in such a position produces 30° of deflection on a compass needle, it is acting with a force equal to half that of the earth (since sine 30° = ·5), and this measures its greatest disturbing power. Similarly, if the same magnet is lying with its centre East or West (magnetic) from the centre of a compass, and at the same distance, but with its length also lying East or West (magnetic), the greatest disturbing power is equal to the tangent of the angle of deflection, which now will be 27° (since tan, 27° = sine 30° = ·5). In either case, if the same magnet in the same position is brought nearer, it will produce greater deflection, and when this equals 90° in the first case and 45° in the second, the magnet is acting with the same power as the earth (since both sine 90° and tan 45° = 1).

The principles involved in these two cases are those embodied in practical electrical measurements, in the construction of (1) sine, and (2) tangent galvanometers.

If a magnet, with its centre above or below that of a compass, is lying with its length in any other position than N., S., E. or W. from the compass, its disturbing power (as measured by the natural sine of the deflection it produces) will equal its maximum disturbing power multiplied by the sine of the angle its line of action makes with that in which it is producing no effect.

Thus, if such maximum power will cause 10° of error, the same magnet, at the same distance, but acting in a direction of N.N.E. and S.S.W. from the centre of the compass, will disturb it 10° × sine 2 points, or 3·7°.

For purposes of correction *only*, it is not absolutely necessary, in many cases, to determine by calculation the original errors of an uncorrected compass, nor, indeed, in the Mercantile Marine is it usual to do so, but in the more complicated cases which occur in warships—especially the first of a new type—it is invariably done.

The original deviations of such a compass are found by the usual nautical process of "swinging ship"; the method by "reciprocal bearings" being less used than those by "distant object" and "sun," owing chiefly to the difficulty of finding positions on shore absolutely free from the effects of local magnetism.

In selecting a distant object to swing by, regard must be paid, in modern long ships, to the diameter of the circle described by the ship, or rather compass, in turning round, as it affords great simplification if the magnetic bearing of the object can be considered practically the same from all points on the turning circle.

If the distance of the object be 350 times the radius of the circle described by the compass, the magnetic bearing will never differ more than 10 minutes either way from its mean value. As during swinging, the view of any *one* point may be sometimes hidden by the ship, it is advantageous to use two objects nearly at right angles to one another, determining the magnetic bearing of one, and then measuring the angle between them with a sextant. Increased accuracy would be attained by using as a distant mark two well-defined objects in transit, or, best of all, two such transit marks nearly at right angles to each other. A list of useful objects for this purpose is given in Lecky's "Wrinkles in Navigation."

Usually, ships are swung on as nearly as possible every alternate compass point, allowing a little time on each stopping point before observing, so that at least an hour should be spent in completely swinging, thus obviating what is termed "Gaussin error," which arises from the horizontal imperfectly soft iron of a ship (*see page* 27) not becoming instantly magnetised and de-magnetised by the earth's horizontal magnetic force as the turning of the ship presents it at different angles to the magnetic meridian. This is especially important in armour-clad vessels, or at compasses in conning towers, and is as necessary a point to consider in a sea-going ship as in one uncorrected. If, however, circumstances necessitate swinging more rapidly, the vessel should be swung twice (turning both to starboard and to port) and the results meaned.

By drawing deviation curves the necessity for swinging on exact points is obviated, and even if the ship be placed on exact points by standard compass, the deviations of other compasses on board from which bearings cannot be taken can only conveniently be obtained by drawing their curves.

Thus (Fig. 5) if at N.E., by standard (A), the deviation of that compass is 5° E., and at the same time the direction of the ship's head, by a compass below (B), is N. 20° E., since the ship is heading N. 50° E., *magnetic*, the deviation of the compass below (B) is 30° E., this being the deviation on N. 20° E. since, in practice, deviation curves are drawn and tables formed for *compass* directions of the ship's head, as shown by the compass considered at the time, Napier's well-known diagram is useful, but not essential, for drawing deviation curves, which may be laid down on ordinary 32-lined foolscap paper (*see* "Manual," pp. 9 and 17). In this way, on originally swinging an uncorrected ship, the deviations of the many compasses on board a battleship are obtained, the principal observer stationing himself at the standard compass, and others at compasses below, noting the apparent direction of the ship's head when signalled to do so.

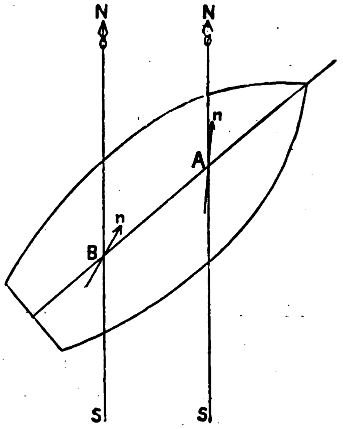


Fig. 5.

The Azimuth Tables and Weir's Azimuth Diagram are so well known to sailors that they require but few remarks in connection with compass correction. Published before modern methods of navigation by lines of position were commonly used, the former are restricted to giving true bearings of heavenly bodies between those altitudes at which they are suitable for obtaining compass errors, such altitudes not exceeding 60°, above which, uncertainty as to the compass card being truly horizontal tends to introduce error into the observed bearing which we wish to compare with that in the Table; this restriction does not exist in the Azimuth diagram.

If finding deviation or total error from amplitude of the sun, it must be remembered that those bearings given in the Tables are calculated for the centre of the earth and on the supposition of there being no atmosphere; if then the daily path of the sun be much inclined to the horizon (as when latitude and declination are both great and of contrary names), corrections for the effects of dip and refraction should be taken from Table 26 of Inman (*see* also Chap. xi. of my Navigation).

Since the true bearing of the sun or other heavenly body at a certain place and time is the same as the great circle course from that place to the position on the earth where the sun or other body is vertical at that instant, Towson's Great Circle Diagram might (as proposed in 1847) be equally well used for determining true bearings, or conversely, either Azimuth Tables or Diagrams might be sometimes used for finding Great Circle Courses.

Although, theoretically, the best position in which to observe the sun for deviation or total error is either when on or near the prime vertical, if latitude and declination are of the same name, or otherwise, when it is low down, as then its movement in azimuth is slow, very good results can be obtained at noon (when, of course, its *true* bearing is either north or south), provided the altitude is not more than about 60°.

During winter months, in the Channel for instance, at noon, the movement of the sun in azimuth is slower than when it is near the prime vertical in the tropics.

In the northern hemisphere at night, the Pole star, if its bearing is corrected from Inman's Tables, will be found very useful for obtaining deviations or total errors.

In order to adjust a compass we have usually to put the ship's head in various *magnetic* directions, which can be done without the aid of a compass, but necessitates generally knowing the magnetic bearing of some distant object.

If such object be the sun, its true bearing (and hence on applying the variation, its *magnetic* bearing) is found from the Azimuth Tables or Diagram; owing, however, to the sun's movement in azimuth it is more convenient, when possible, to use a distant terrestrial object.

The bearing of this may be (1) sometimes taken directly from the chart; (2) obtained by measuring the horizontal angle between it and the sun, using for the purpose of such measurement either the azimuth circle, bearing plate or, for very exact observations, the sextant; or, (3) in cloudy weather, by taking the mean of four or more compass bearings taken on equi-distant compass points if the compass is in the midship line.

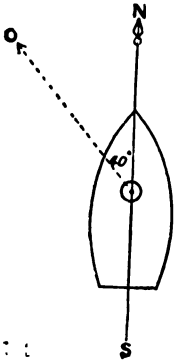


Fig. 6.

If a *very* distant object be used and its magnetic bearing found by either methods (2) or (3), this will generally differ from that taken off a Mercator Chart by the same amount and for the same reason that a great circle course to it would differ from a rhumb course.

If, then, the magnetic bearing of the object found in either of these ways be N. 40° W., when the ship is moved so that the object O is 40° on the port bow (Fig. 6), her head must be North magnetic, and if moved so as to bring the object 50° on the starboard bow it will be West magnetic.

If, then, while the ship is lying with her head in *any* direction the azimuth mirror is turned through the calculated angle on either bow (read off on the azimuth circle), on looking through the prism and turning the ship, her head will be in the desired magnetic direction when the object is seen on the pointer, independently of the card altogether.

The same result will be attained by using the dumb card (known also as the Pelorus or Bearing Plate), which, as the first name implies is a compass card without needles turning on its centre (Fig. 7); an outer concentric fixed ring has on it a mark (C) corresponding to the lubber line when the box containing the instrument is placed in certain prepared positions on board, one of which is usually the end of the bridge. If, then, we wish to put the ship as before, with her head North magnetic, the dumb card is turned until the North point is under the lubber line and the sight line A B set to N 40° W; on looking through A as the vessel is turned, when the object is seen in the direction A B, the ship must be heading North magnetic.

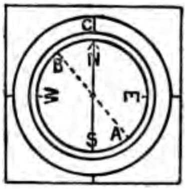


Fig. 7.

As the only practical way, at sea, of finding the variation is by comparing the magnetic bearing of the sun (as found by meaning equi-distant compass bearings) with its true bearing, it is evident that swinging for deviation at sea, provides at the same time, with most well placed compasses, the material for finding the variation also, and it is from such observations, taken with every possible accuracy, that the variation chart is principally drawn.

Throughout the following lectures we shall generally suppose that we are dealing with a compass placed in the midship line, and also (until the last two lectures) the ship will be considered upright.

It will be also more clear in dealing with the various sources of compass error if we consider them first as acting one at a time, but not in the order in which they are corrected.

Finally, they will be dealt with in the combined form in which in practice they are met with.

The compass will be supposed to be one (such as the Thomson compass) having needles so short that their lengths may be neglected as compared with the distances of either the nearest disturbing iron in the ship or that of the nearest corrector employed.

The former condition is practically attained with Thomson's 10″ card at a distance of 7 feet, and the latter in the case of

(1) corrector magnets at a distance of twice the length of such magnets, measured from centre of compass to middle of magnet; (2) with Flinder's bar (24 ins. long), by keeping the upper pole 9 ins. distant from the centre of the compass; and (3) with the soft iron spheres, by keeping the nearest points beyond a distance of one and a quarter times the length of the longest needle from the centre of the compass.

Thomson's binnacle is purposely constructed so that such minimum distances cannot be encroached upon.

EXAMPLES.

1.—Thomson's compass and the Admiralty standard compass were designed for the same general purpose; why do they differ so much in appearance? Draw rough figures of them.

2.—Sketch the arrangement and fittings of a binnacle for a standard compass.

3.—Explain with figures the various ways of swinging ship both when in and out of sight of land.

With ship's head S. 10° E. by standard, the compass bearing of a distant spire was found to be N. 40° E., its true bearing being N. 60° E., variation 10° W. Find the deviation of a main deck compass by which the ship was heading S. 15° W. at the same instant, illustrating your answer by figures? *Ans:*—5° E.

4.—The bearing of a distant object is S. 56° E. It is required to place the ship's head successively East and South (magnetic) for correcting the standard compass. Describe how the azimuth circle of the compass can be utilized for that purpose, as also the bearing plate (Pelorus).

5.—Draw figures showing what is meant by "broadside on" and "end on" positions of a magnet.

6.—At sea, from a compass in the midship line, the following compass bearings of the sun were observed:—S. 65° E. (head north); S. 54° E. (head south); S. 63° E. (head east); S. 51° E, (head west); the mean true bearing of the sun being S. 60° E. What was the variation? *Ans:*—1¾° W.

LECTURE II.

Effects of Hard Iron—Action on Different Points—Change of Position—Correction by Magnets—Sub-permanent Magnetism.

The deviation of an uncorrected compass is always the combined effect of three, and in some cases of five separate causes the action of each of which may be graphically represented by a curve, the one original curve or table being really formed by the union of three or five independent curves or tables; it is the function of the adjuster to separate out from this one original its various components and apply suitable individual correctors for each; so that when we examine the curve of a corrected or nearly corrected compass, the original state of matters is completely disguised. Although each component of the original gives by itself a perfectly regular curve having usually two or four loops, the combined curve is generally one of great irregularity We propose in this and subsequent lectures to trace through to their consequences each of these causes separately, that is, we will suppose only one to be acting at a time and then finally discuss their united effect, which of course is always that observed in practice.

Iron from a magnetic point of view is usually spoken of as being "hard" or "soft," terms which are very ill chosen, as they indicate properties altogether different from those usually associated with these words. Hard iron (with which we shall exclusively deal in this lecture) is that possessing permanent magnetism, and, in an iron ship, apparently obtaining this property chiefly by the process of hammering when cold, since we always find the skin of the ship the principal seat of this cause of disturbance.

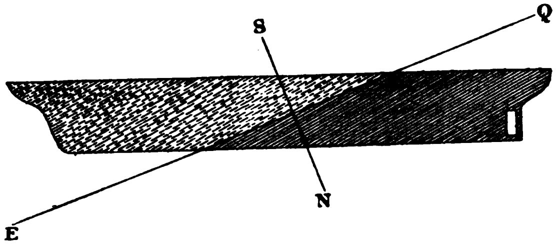
By the process of rivetting, each individual iron plate acquires an amount of magnetism, usually at first in excess of what itcan permanently carry, but which gradually settles into a constant amount; their united effects last as long as the ship, and being caused by permanent magnetism, can be accurately corrected by permanent magnets.

The preliminary steam and gun trials of vessels of war usually, as it were, "shake out" the overdose of magnetism referred to, so that on going on sea service this part of the deviation has generally assumed a permanent character; unfortunately this is far from being the case with many new merchant vessels, which are often hurried off on a first voyage with compasses greatly affected by temporary magnetism, and though at starting this may be disguised by correctors, it very soon escapes, developing large errors due to erroneous over correction, which errors circumstances of weather might prevent the navigator from observing and allowing for, to the serious risk of the ship.

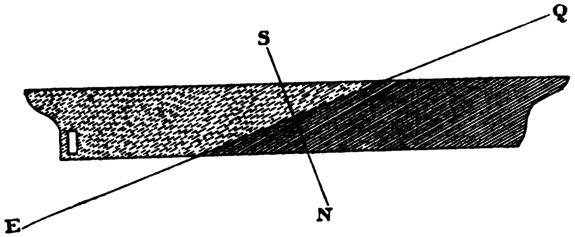
With lapse of time the athwartships magnetic action of the ship generally changes most rapidly, probably because at a standard compass it is principally due to hard iron, while the fore and aft action may be largely caused by vertical soft iron, which, while the dip remained the same, probably alters less than the hard iron. On change of *position* as the dip generally alters, the fore and aft magnetic action of the ship will probably change as much, or more than the athwartships action.

As iron of the "hard" character was for many years practically the only kind used in ship building, the earlier

Head South.



Head North.



Head West. Head East.

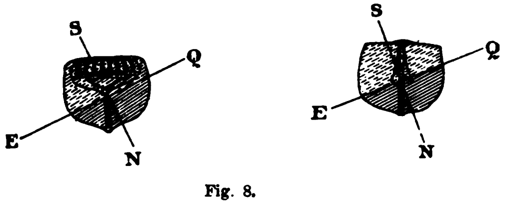


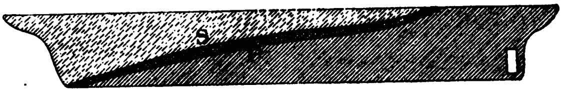
Fig. 8.

THEORETIC MAGNETIC CONDITION OF IRON SHIPS BUILT IN ENGLAND WITH THE DIP OF THE NEEDLE FROM 68° TO 70° NORTH PREVIOUS TO BEING LAUNCHED.

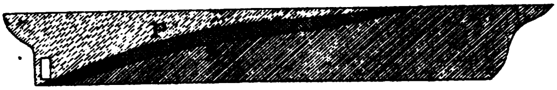
The line S.N. in each figure represents the direction of the Dip or line of magnetic force as passing through the general centre of gravity of the material of the Ship.

All below the line E.Q, shaded with firm lines, has Northern or red polarity; all above it, shaded with broken lines, has Southern or blue polarity.

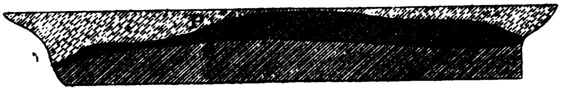
Bœotia.
Built head to South (a little West).



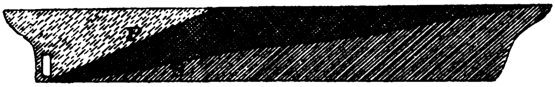
City of Washington.
Built head to North.



Sarah Palmer.
Built head to East (a little North).



Borysthene.
Built head to N.E.



Barcelona.
Built head to S. W.

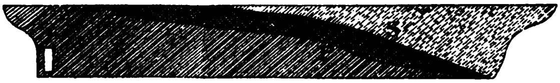


Fig. 9.

MAGNETIC CONDITION OF VARIOUS IRON SHIPS, RESULTING FROM ACTUAL EXPERIMENT, AS DETERMINED AT LIVERPOOL BY THE COMPASS COMMITTEE, 1856-7.

Note.—*The letters P and S denote the Port and Starboard lines of no Deviation.*

investigations in compass correction were mostly directed to ascertaining the effect of the skin of a ship on a compass placed on board, and in 1854-7 the well known Liverpool Compass Committee magnetically examined many iron ships by carrying a compass all round them, inboard and outboard, at a certain fixed distance, and noting the disturbances caused.

The result of their investigations (confirmed by much subsequent experience) shows that in the process of building, an iron ship is converted, as a whole, into what ultimately acts both internally and externally as a permanent magnet, lying very approximately in the plane of the magnetic meridian at the place of building and also in the line of dip, having its red pole to the north and blue pole to the south, but whose position with regard to the fore and aft line of the ship depends upon the direction of her head when building.

Some of the evidence on which this very important statement is based is graphically shown on Figs. 8 and 9, which should be carefully studied and compared.

If, after launching, the ship be subjected to much hammering with her head in any other direction the original position of this "ship magnet" may be considerably modified.

We might then, with regard to this first cause of error, suppose the compass placed between the poles of a large magnet which will turn round with the ship, and at first we will assume her to be upright and the compass in the midship line. Suppose an iron vessel to have been built in the northern magnetic hemisphere, with her head N.W. magnetic, then her permanent magnetism would be represented as shown on Fig. 10, that is, her hull would act on a compass A on board as though there was a permanent blue pole (S) high up on the port quarter, and a red pole (N) low down on the starboard bow, which poles being, as it were, fixed in the ship, move with her, and might be expected to produce their greatest effect on a compass placed *between* them, and similar but lessened effects on compasses placed elsewhere in the ship, since the action of a magnet is always parallel to itself; obviously, if we could place a smaller magnet near the compass, with its poles in the opposite direction to those of the ship herself, the disturbing effect would be annulled, but as there are great difficulties in doing this we, in practice, deal *separately* with each component of this ship's force.

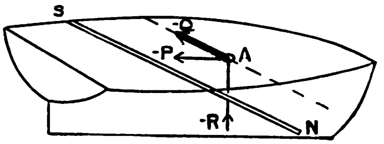


Fig. 10.

Thus, at a compass on the upper deck in the fore and aft line placed at A, the one magnetic force of the ship supposed to act through A, and parallel to S N, will be equivalent to three generally unequal forces acting in this case to the stern, to the port side and upwards, these forces are usually denoted by the letters P, Q, and R, and considered to be positive (+) when acting to the bow, starboard side and (when upright) to the keel, and negative (−) when acting in the opposite directions, so that in the present case the compass is affected by − P, − Q and − R; if, at first, we suppose the ship upright, R will produce no deviation and may be disregarded, being more appropriately considered when we deal with the heeling error.

On this supposition our figure might be simplified by supposing P and Q to be acting in the plane of the compass or, as it were, on the upper deck (Fig. 11 *a*), in which case their united effects may be represented by a magnet, R B, lying in the magnetic meridian when the ship's head is N.W. or S.E. (compass or magnetic since at these points there is no error).

To trace the changes in deviation from this cause as the ship turns round, no effect will be produced with the head either N.W. or S.E. (compass or magnetic), but the greatest result, say 10°, will occur when the ship swings so as to bring the magnet R B broadside on to the compass needle *(see page* 6) which will occur when heading S.W. and N.E. (compass, *not* magnetic) being easterly in the first case and westerly in the second (Fig. 11 *b*). If, then, the compass has very short needles, a regular curve, such as that shown on Fig. 12, will result, which is appropriately called a semi-circular curve having its neutral points or those of no deviation in the direction of the ship's head when building, and the opposite, and its maximum effects occurring at eight points (by compass) from these, such maxima being easterly or westerly, according to the obvious law that the part of the ship which was South (magnetic) when building always has blue magnetism.

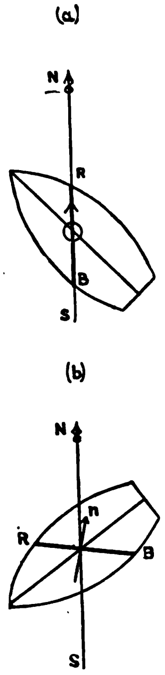


Fig. 11.

Such curves are drawn on the supposition that the central line represents the straightened edge of the compass card, as ships are in practice always swung on *compass* and not magnetic points.

The deviation from this cause on *any* point may be approximately found from the rule applicable to all semi-circular curves, that such error equals the maximum deviation produced, multiplied by the sine of the number of compass points from the nearest neutral point.

Thus, in the foregoing case, the deviation at S.S.W. (compass) will be approximately 10° × sine 6 points = 9° and will obviously be easterly, while that at North (compass) will be 7° westerly.

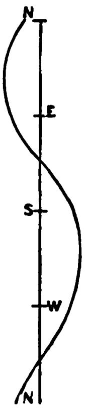


Fig. 12.

To illustrate this, if Fig. (13 *a*) represents the ship with her head S.S.W. by compass, the north end of the needle will evidently be drawn to the eastward by the ship's magnetism, the poles, R B, turning, of course, with the ship.

If, then, we take a length, A B, on the magnetic meridian to represent the magnetic horizontal force at the position of the compass *(see page 67)*, and measure B C on the same scale, parallel to R B, and equal to the *total* power of R B (that is, both the attractive effect of B on the north pole of the needle and the repulsive effect of R), then, on joining C A, the angle B A C will be the deviation produced.

From the figure we see that sin B A C : sin B C A :: B C : B A.

But as B C A = N B C − B A C, it equals the *compass* direction in which R B is pointing, so that, if we consider B A = 1, sin dev. = force of ship's magnetism × sin compass angle from the direction of the ship's

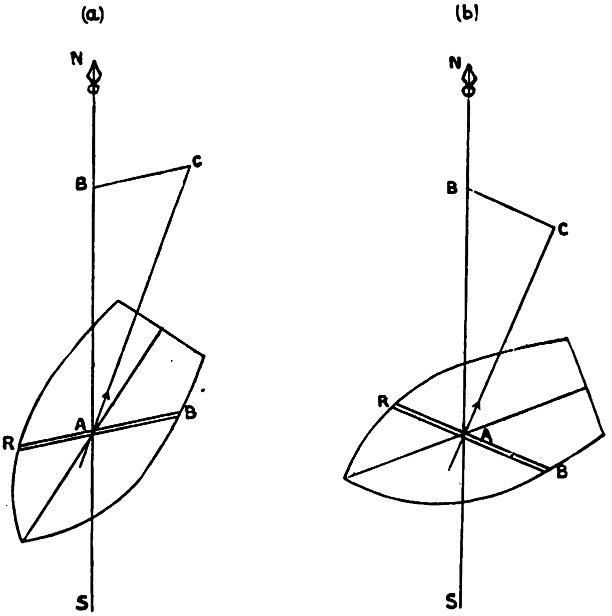


Fig. 13.

head, when R B was in the magnetic meridian or, in other words, from its nearest neutral point.

On referring to Fig. (13 *b*), we see by making the same construction that when the ship swings so as to bring R B to lie East and West by compass it produces its maximum effect, and B C or force of ship's magnetism = B A or 1 × sin deviation.

Hence the deviation on any point (or strictly speaking its sine) equals the maximum deviation (or strictly speaking its sine), multiplied by the sine of the compass angle from the nearest neutral point.

Instead of dealing as above with the united effects of P and Q we might have done so with each separately, drawing their individual semi-circular curves and then uniting them, which will give the same result; the neutral points of action of P being at north and south by compass, and those of Q at east and west, the maxima of P occurring at East and West and those of Q at North and South (all *compass* points).

In tracing the changes in deviation produced by the hard iron, as the ship alters her position in the world we must remember that the magnetic force of the ship when settled down is permanent, and will be equally powerful in *itself* at either magnetic pole or at the equator, but the pointing power of the compass, which is now always suspended horizontally, is dependent on the horizontal force of the earth's magnetism, which is very different at different places on the earth, varying roughly speaking from nothing at the magnetic poles to a maximum on the magnetic equator.

The magnetic force of the earth is of course everywhere acting in only *one* direction, but for compass work it is more convenient to think of its two components, one vertical (V), the other horizontal (H). In London a magnetic needle suspended by its centre of gravity points (1906) about 16° west of true north, and the north pole dips about 67° below the horizon, so that if A B (Fig. 14), represents T, the earth's total force, A C or H will represent in London the horizontal, and A D or V the vertical component, the former in London being much smaller than the latter. These components are equal in dip 45°, which is found in the West Indies and on N.E. coast of Australia.

The connection between these forces is :—

$$\text{A C or H} = \text{A B or T} \times \cos.\ \text{C A B or dip.}$$
$$\text{A D or V} = \text{A B or T} \times \text{sine C A B or dip.}$$
$$\tan\ \text{C A B or dip} = \frac{\text{B C}}{\text{C A}} = \frac{\text{D A}}{\text{C A}} = \frac{\text{V}}{\text{H}}$$

In the south magnetic hemisphere, S dips below the horizontal plane, and at the magnetic equator N S lies horizontally and there is no vertical force.

As a guide to the navigator, charts (such as No. 3 of the Manual or Chart 1 at the end of this book) are published, on which, by taking the horizontal force at Greenwich as the standard (expressed as unity), that at other places is shown in terms of this standard by curves in a similar way to those familiar to all sailors on the Variation Chart; an examination of this chart of Lines of Equal Horizontal Force shows that except on the coasts of Canada and Newfoundland, within the limits of ordinary navigation the horizontal force of the earth's magnetism everywhere exceeds what it is in England, attaining to double that amount over the East Indies; from which it generally follows that during a voyage the deviation from hard iron on any one point (or the maximum deviation from that cause) should be less than in England, for, evidently, if the permanent magnetism of the ship disturbs a compass, say 10° on a certain point in England, it will only affect it 5° on the same point at Bombay, as the horizontal force—on which the pointing power of the compass depends—is then doubled. The very smallest amount of permanent magnetism in a ship would produce such effects at the magnetic poles, where the earth's horizontal force is *nil*, that the north point of the compass would always point to the pole of the ship.

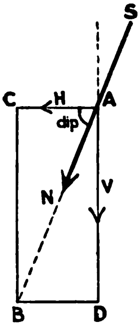


Fig. 14.

As a further illustration of the above, suppose that a vessel sailing from England to Queensland, *via* the Cape of Good Hope, has 6° of westerly deviation with head South at starting.

On that point, as she proceeds south in the Atlantic, her deviation will decrease (since the horizontal force of the earth is increasing), until in lat. 10° N. it will be about 4° W., having decreased in the proportion of 1 to 1·6 (see charts above referred to). After this, it will, on the same point, again increase, until off the Cape, about the same will be found as in England, practically remaining 6° W. on the south point while crossing the Indian Ocean, and gradually reducing to about 3½° W. at Brisbane. Change of position, it will be observed, alters the *amount*, but not the *sign* of the deviation, which, if westerly anywhere, is on the same point westerly everywhere, and *vice versâ.*

If accurately corrected in England by permanent magnets, though change of position might alter the pointing power of the compass, it will not introduce deviation from this cause.

In practice it must be remembered that the effect of sub-permanent magnetism *(see page 24)* might partially or wholly temporarily disguise the above effect.

The correction of the error arising from hard iron is our first application of the principle of "like curing like"—bar magnets which themselves would cause semi-circular error, being so placed as to exactly counteract the similar kind of error caused by the permanent magnetism of the ship.

Theoretically, as we have seen on reference to fig. 10, if at each compass in the ship we could place a small magnet in a position parallel to S N but with its poles oppositely directed, we could neutralize all the disturbance arising from the hard iron both horizontal and vertical, but as it is difficult to exactly determine the position of S N, it is in practice more simple to correct its three components separately, and if we at first consider the ship upright this resolves itself into applying permanent magnets to correct the forces we have called P and Q.

By one of the methods previously described *(see page* 10), suppose we place the ship with her head North magnetic (Fig. 15) and find that the north end of the needle is drawn to port, or, as we should say, the compass has westerly error; this can only arise in the case we are considering, of a compass placed amidships, from the ship having permanent athwartships magnetism with blue on the port side, or, in more technical language, the compass is acted on by a force $-Q$ (the fore and aft component of the hard iron obviously producing no deviation *directly*, though it will do so indirectly, by increasing or decreasing the pointing power), the compass may therefore be corrected by placing a magnet, A, in an athwartships position on the fore and aft line with its red pole to port, and moving this to and fro if on the deck, or up and down if in the binnacle, until the *compass* bearing of the distant object is the same as its magnetic bearing, when, if the ship's head is exactly North magnetic, the north point of the compass card will be under the lubber line.

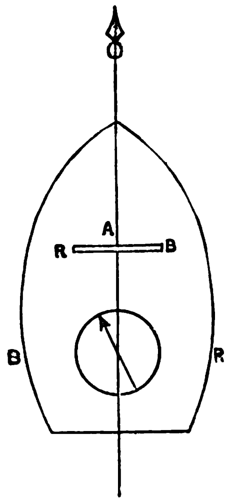


Fig. 15.

It is often difficult, unless under weigh, to keep a heavy ship with her head *exactly* on any point for a sufficiently long time to accurately adjust, especially if, as usual, we have to deal at the same time with several compasses, so that if in this case the ship's head, at the time of correction, is N. 4° E. magnetic, the magnet, A, must be moved until, as before, the compass bearing of the distant object agrees with its magnetic bearing, but the ship's head by compass is N. 4° E.

It is immaterial whether the magnet, A, is placed before, abaft, above or underneath the compass, provided that it is kept at a fixed distance measured from its centre to that of the compass; but in practice most binnacles are purposely constructed so as to carry the corrector magnets for greater safety and covenience in holes (or movable racks) underneath, and as it is advisable to keep these magnets as far away as possible, it is best to begin by filling up the lower holes first, working upwards as required.

The limit of nearest approach for these magnets is twice their own length, as measured from middle of magnet to centre of compass *(see page* 11*)*, within such distance the action on *both* poles of the compass would practically come into play and cause more inconvenient errors than those we are seeking to cure *(see page* 43*)*. In Thomson's compass the absence of holes prevents this limit from being encroached upon; the error thus corrected at a compass in the midship line is technically known as that caused by co-efficient C; at a compass out of such line it is only one part of this co-efficient *(see page* 57*)*.

The ship is next turned until her head is East magnetic (Fig. 16), when, on the supposition that only hard iron is acting, if the needle stands as in the figure, we conclude it is disturbed by the fore and aft permanent magnetism of the ship having blue in the aft part (– P). This deviation is corrected by magnets placed in pairs, beginning in the lower fore and aft holes of the binnacle, or in corresponding positions on either or both sides of the deck, with their red poles aft, using the same precautions as before, and in all cases making the compass bearing of the distant object exactly agree with its magnetic bearing.

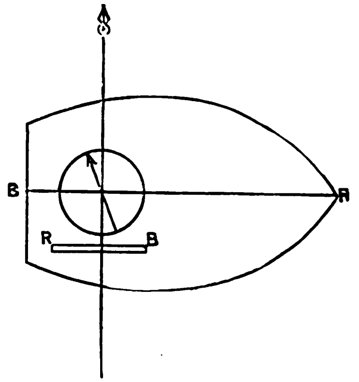


Fig. 16.

The error now corrected is a part of that known as the effect of co-efficient B.

It is immaterial, theoretically, on which cardinal point we first put the ship's head or which is corrected first, B or C, but if otherwise equally convenient, it is better to begin with the greater, and thus steady the compass.

In the case we have taken, on subsequently placing the ship's head South and West magnetic, there should be no practical error in the compass, and if any is found we might reasonably attribute it to some error in observation, or to having used a wrong magnetic bearing to swing with, which probably might arise from the application of a wrong variation.

As experience shows that this occasionally occurs when adjusting a sea-going ship abroad, at places where the variation is not well known, suppose a case where a ship has been corrected by using a distant object whose magnetic bearing is considered to be S. 40° E., the resulting deviations on the cardinal points being: North 0°, East 0°, South 4° E., West 4° E. In such a case, although we can always move the magnets so as to have no errors on two *adjacent* cardinal points, it will be found impossible to move them so as to have no errors on both of two *opposite* points, though we can easily manipulate them so as to have the *same* error of 2° on *each* of the four points.

This error, if the observations are good, will represent the error in the bearing, or, usually, in the variation, used.

Thus, if the bearing of S. 40° E. had been obtained on the supposition that the variation was 10° E., then the real variation was 12° E., or, if the supposed variation was 10° W., in reality it must have been 8° W.

Practically, at a compass in the midship line, such error is immediately detected on swinging a sea-going ship by taking the algebraical mean of the deviations found on any four, eight, or more equidistant compass points, when, if the result amounts to, say, more than half a degree, some error in the variation used might be justly suspected.

In the rare case of having no means of putting a ship's head on magnetic cardinal points, the compass (if the deviation be not excessive, or above 20°) might be corrected by putting her head repeatedly on compass points, introducing magnets as though on corresponding magnetic points.

Thus, if the ship is heading North by compass, and from the bearing of the sun, or other means, the deviation is found to be 12° E., if athwartship magnets, red to starboard, are introduced until the north point is driven, approximately, 12° to port, on again placing the ship's head North by compass, probably only a small further similar correction will be needed.

By thus repeatedly placing the ship on the same compass point and moving the magnets as required, ultimately the compass and magnetic directions of her head will coincide and the correction will be effected.

It will be observed, on reference to Fig. 11 *(page* 17), that instead of using two magnets broadside on to correct with, one only might have been employed, placed at such an angle with the fore and aft line as to neutralise the resultant, or combined action, of P and Q. Originally, in the Royal Navy, it was customary to do this, but the former, original, and more simple method, is now everywhere used.

It will also be noticed that the corrections *could* be made by using horizontal magnets, *end on* to the compass on either or both sides, with the advantage of keeping them much farther off, or even vertical magnets might be employed; but, as in such positions the poles of the magnets would not be equidistant from the centre of the compass (as they necessarily are when broadside on), vertical forces, and therefore heeling errors, would be introduced.

It should be remembered that these corrector magnets are placed for the purpose of always balancing the horizontal permanent magnetic forces of the ship, whether upright or rolling, so that they are necessarily placed where they participate in every movement of the ship, although the compass card itself always remains horizontal.

In the case we have considered, where the correction is accurately made, the compass will point as truly on board as on shore.

The reduction of the mean pointing power of a compass, always found to exist on board an iron ship *(see Lecture* VI*)*, will cause the magnets used for correcting semi-circular error to produce greater effects on board than on shore, under, of course, exactly the same circumstances of position and distance from the centre of the compass; the reason for this being precisely the same as that which explains the varying effects in different localities on the earth of the permanent magnetism of the ship.

When a sea going iron vessel steams for a long time on one course, the vibration caused by the machinery, together with the motion of the waves, tends to produce a temporary magnetization of the hull of a precisely similar character to that originally caused in the ship by hammering, that is to say, a temporary red pole will be induced on the side towards magnetic north, and, therefore, always north of the compass whatever her course might be, and a temporary blue pole on the side towards magnetic south.

This effect by itself would cause temporary semicircular deviation, and if the ship were swung it would be found that while no change in the original deviation existed on the points corresponding to the course and that opposite, considerable alterations might take place on those points at right angles to the course.

The amount of such change of deviation varies much in different types of ships, being intensified by long continuance on one course and by excessive vibration, attaining, for instance, values of many degrees in a short time in "destroyers"; on the whole it is most noticeable when, after steering east or west for some time, course is altered to north or south.

Corresponding effects are produced more slowly when a ship remains in harbour with her head in one direction for a long time, and similar changes are also rapidly produced by firing heavy guns on board; indeed, any cause which occasions tremors in a mass of iron renders it more susceptible of temporary induction by the earth.

Such changes are attributed to what is appropriately called "sub-permanent" magnetism, and its temporary character, combined with the fact of its never giving any indication of its existence while a ship is steering the same course, renders it a serious consideration in modern navigation. The length of time during which the effects of this temporary error remains varies greatly, from a few hours to a few days, under different circumstances and in different ships, but a good idea can be found of what is taking place by occasionally, when circumstances admit, observing the deviation with the ship's head eight points from the original course, and also taking the precaution, before permanently altering course, of putting the ship's head in the new direction and observing the actual deviation, more especially if the new course will have to be shaped at night.

No corrector for this dangerous source of error has yet been devised, and its varying character greatly emphasizes the necessity for frequently observing the errors of a compass.

As an illustration of the effect of sub-permanent magnetism when not allowed for, suppose, in Fig. (17 *a)*, a vessel steering N.E. at a high speed the deviation being 2° E.

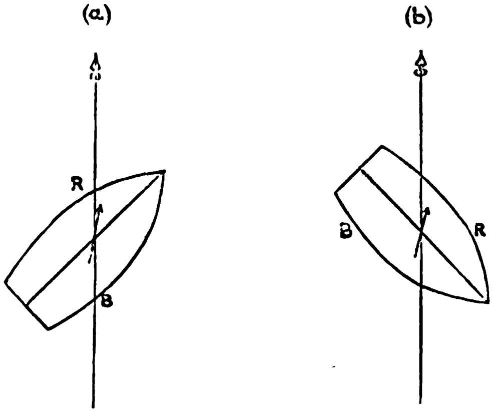


Fig. 17.

A red pole is being developed on the port side of the ship, but as it is north of the compass the deviation remains unchanged until course is altered to, say, S.E. Fig. (17 *b)*. By doing this the induced red pole in the ship is brought at right angles to its former position and the north end of the needle driven to the westward, thus *increasing* westerly deviation at S.E. if it originally exists, or decreasing original *easterly* deviation, so that if course is altered to S.E., on the supposition that the original deviation on that point is unaffected, the ship will go to the eastward of what is intended.

This affords an illustration of the universal fact that if no allowance be made for sub-permanent deviation a ship on alteration of course will almost always tend to go in the direction of her last course.

The cause of this kind of compass error was formerly known by the singularly inappropriate name of "Retentive" magnetism, its most dangerous feature arising from its not being retentive.

EXAMPLES.

1.—Given an iron rod, how would you practically ascertain if it possessed "permanent" magnetism?

2.—If at a compass P (or fore and aft permanent magnetism) = + 10°, and Q (or athwartships permanent magnetism) = − 5°, draw their individual and combined curves, stating the probable direction of the ship's head when building, and also showing how the compass might be corrected with *one* magnet.

3.—A compass has in England a maximum error of 10° arising from "hard" iron; what would the maximum be at (1) Quebec, (2) Jamaica, (3) Cape Horn, (4) Cape of Good Hope, (5) Singapore, (6) Yokohama.

Answer:—12°; 6°; 7°; 10°; 5°; 7°.

4.—In the following cases, an erroneous variation having been used when determining the deviation, it is required to find the deviation, using the correct variation—

Variation.		Deviation by
Erroneous.	Correct.	using incorrect variation.
10° E.	8° E.	10° E.
24° W.	22° W.	18° W.
10° W.	8° W.	15° E.

Answer:—12° E.; 20° W.; 13° E.

5.—A ship is found to have a deviation of 10° E. with head East, the variation used being 18° E. What would the deviation be, if the correct variation was 20° E.?

Answer:—8° E.

6.—A deviation table was obtained for a standard compass round which the iron was symmetrically distributed. To obtain the magnetic from the true bearing of the distant object observed, an assumed value of 5° westerly variation was allowed. If the mean compass bearing differed from the magnetic bearing by + 2°, what was the correct variation at the place?

Answer:—7° W.

7.—A vessel after steering westerly courses for some days in the Mediterranean alters course to North when clear of the Straits of Gibraltar; how would sub-permanent error affect her?

LECTURE III.

Vertical Soft Iron—Representation by Soft Iron rods—Action of Soft Iron—Flinder's Bar—Separation of parts of Semi-Circular Error.

If we examine the magnetic condition of a mass of iron which has not been hammered much (or at all), when cold—say an armour plate—by carrying a small compass round it at a constant distance and observing the effect produced, we find that if A B is the line of dip at the place of experiment (Fig. 18), and C D an imaginary plane at right angles to A B cutting the plate in halves, the upper part in the northern hemisphere will act on the experimental compass as though it possessed blue magnetism, and the lower part as though it were red; if the plate be now capsized the part at first on top and blue is now underneath and red, and that at first underneath and red is now on top and blue, so that the action of the plate in either position will be that of a magnet, X Y, lying in the plane of the magnetic meridian and inclined to the horizon at the angle of dip, always having blue at X or on top, and red at Y, or underneath. This is, of course, precisely similar to the original condition of the skin of the ship, as a whole, considered in our last lecture. At the magnetic equator X Y will be horizontal, since the line of dip is horizontal there, and at a position in the southern hemisphere where the dip is equal, but opposite to that shown in Fig. 18, the poles of X Y will be reversed.

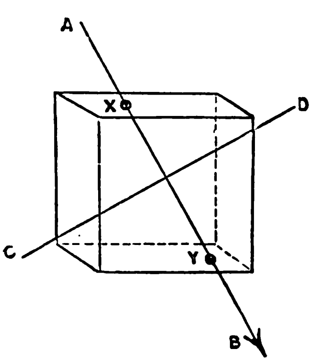


Fig. 18.

Iron capable of being magnetised by the earth or by any other magnet in this way (called induction) is known as "soft" iron, and has been defined as "malleable iron which has not been hammered when cold."

Experience and experiment show that no iron on board ship is either absolutely soft or hard, but the former character greatly preponderates in beams, armour and decks, and the latter in the skin of the ship.

On referring to Fig. 18 we see that, except at the magnetic equator and poles, we might always consider X Y as producing both a vertical and horizontal effect, and might accurately represent the magnetic action of the armoured plate by two temporary magnets, one vertical with (in the northern hemisphere) blue pole up, and one horizontal with (in either hemisphere) blue pole south; in this lecture we shall consider the action of the vertical component alone, and when we reflect that all iron which has not been hammered much when cold will behave similarly to this armour plate, we see that these united effects will be such as would be caused by (in the northern hemisphere) a blue pole, B, in the fore and aft line, situated somewhere in the ship below the plane of the upper deck, and this will act on compasses placed anywhere in the ship, exactly as if fine strings were fastened to their north poles and pulled in the direction of B (Fig. 19), producing at all compasses on the upper deck a downward pull and at compasses (1) and (3) a fore and aft pull, to the bow at (1) and to the stern at (3).

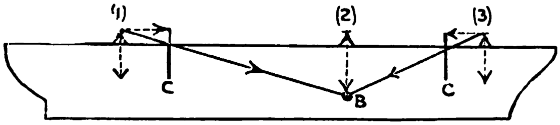


Fig. 19.

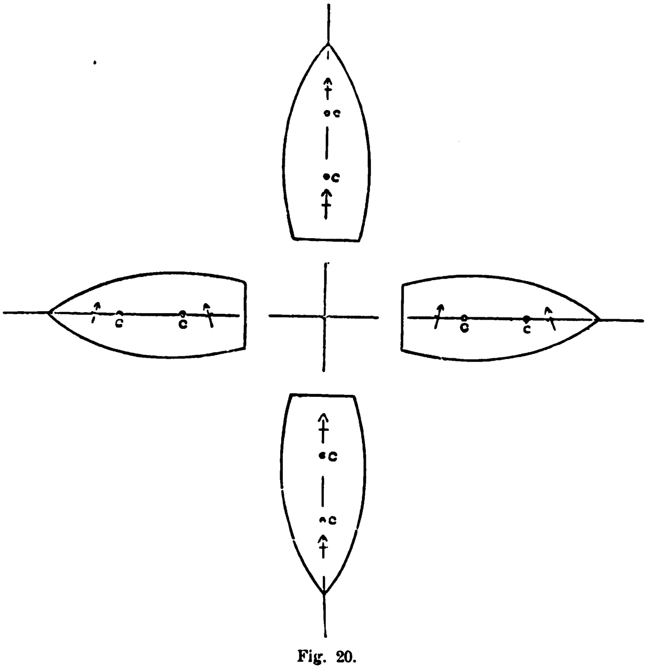


Fig. 20.

The downward pull produces no deviation when the ship is upright, but forms one important cause of heeling error, and will be considered in Lecture VII., where its action is represented by that of a vertical soft iron rod *k*; the fore and aft force at (1) might be accurately represented by a thin, soft iron rod (*c*), placed vertically and in the northern hemisphere, necessarily with its blue pole upwards, such pole being in the plane of the compass and forward of it at (1), and abaft it at (3).

In the southern magnetic hemisphere, such an imaginary rod will have a red pole upwards.

Taking, then, either compass (1) or (3) as an example, we see from Fig. 20 the error from this source will vanish with the ship's head North or South by compass, and be at its greatest with head East or West by compass.

This is true for each of the compasses on board, so that if the ship is swung and the observed deviations plotted on a curve, compasses situated like (1) will give curves similar to Fig. (21 *a*), and those situated like (2) curves similar to Fig. (21 *b*), these being semi-circular curves following the law of all such curves, viz., that the deviation on any point approximately equals the maximum deviation multiplied by the sine of the angle from the nearest neutral point, which in this case means the sine of the compass course.

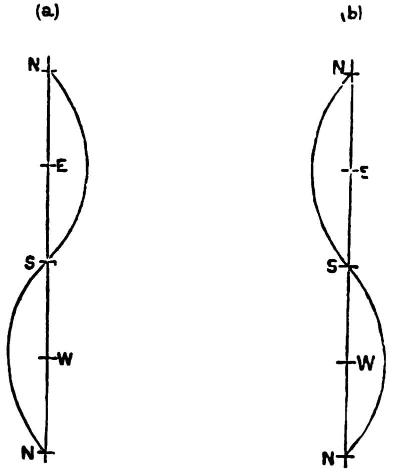


Fig. 21.

Thus, if the maximum error from this cause be 10°, the amount acting with the ship's head N.E. will be 10° × sine 4 pts. = 7°. It must be noticed that the soft iron rod (*c*) referred to is one which is purely imaginary, and is supposed to have no thickness, so as to be magnetised only by the vertical component of the earth's force; this consideration of infinitely thin rods is applicable to the many cases where various kinds of magnetic actions arising from soft iron are conveniently represented by either vertical or horizontal rods, the *forces* which these represent are, of course, very real, and we can in imagination as well represent these forces by such rods as we depict the track of a ship on a chart, or the direction of an object by a line. The whole of the effect of the soft iron of a ship on a compass, whether the vessel be upright or heeled over, can be, as we shall see, accurately represented by the actions of some, or all, of nine such soft iron rods, three vertical and six horizontal, which are supposed to be magnetised by induction from the earth *(see* Fig. 22).

Of these soft iron rods at an ordinary standard compass when a ship is upright, only those termed *a*, *c* and *e* are acting, but at a binnacle compass out of the midship line, rods *b*, *d* and *f* act in addition to these; rods *g* and *k* do not cause deviation until the ship heels and rod *h* is practically non-existent. Two cases for each rod are shown, one in which positive (+) effects are produced, and the other negative (−), only one case, of course, being applicable to any particular compass.

Being supposed to have no thickness, horizontal rods will be magnetized by the earth's horizontal force *only*, and similarly, vertical rods by vertical force *only*.

Thus, if a rod *(a)* is said to have a value of ·1, this means that when most favourably placed for induction by the earth (that is when lying north and south magnetic) it will have induced in it $\frac{1}{10}$ of the earth's horizontal force at the place where the ship is, such amount depending chiefly on the quality of the iron considered.

If a rod *(c)* has a value of ·2 this means that the earth's vertical force is inducing in it $\frac{2}{10}$ of its own vertical power at the place considered.

The effects of horizontal rods in *producing deviation* at any particular place will depend both on their own power and on the angles their lengths make with the magnetic meridian. Only the ends of the rods nearest to the compass are supposed to act when they are on either or both sides of it.

The effect of vertical soft iron rods in causing deviation will depend both on their own power and also on the horizontal force of the earth, and therefore vary as the dip. The plus and minus signs used must not be supposed to indicate easterly and westerly errors, but only *opposite* effects when in different positions.

The effect of soft iron rods as compared with those of hard iron may be further illustrated as follows.:—

A thin round rod of soft iron pointing North magnetic and inclined with the end towards north, at an angle below the horizon equal to the dip (67° in London), will be magnetised by the *total* force of the earth, which will cause the lower end, in England, to be red and the upper blue.

(1).—Suppose this rod to be placed with its upper end in the plane of a compass (having very short needles), and East of its centre at such a distance as to cause 10° of deflection.

(2).—On keeping the upper end in exactly the same position, but lowering the north end until the rod is vertical, it will

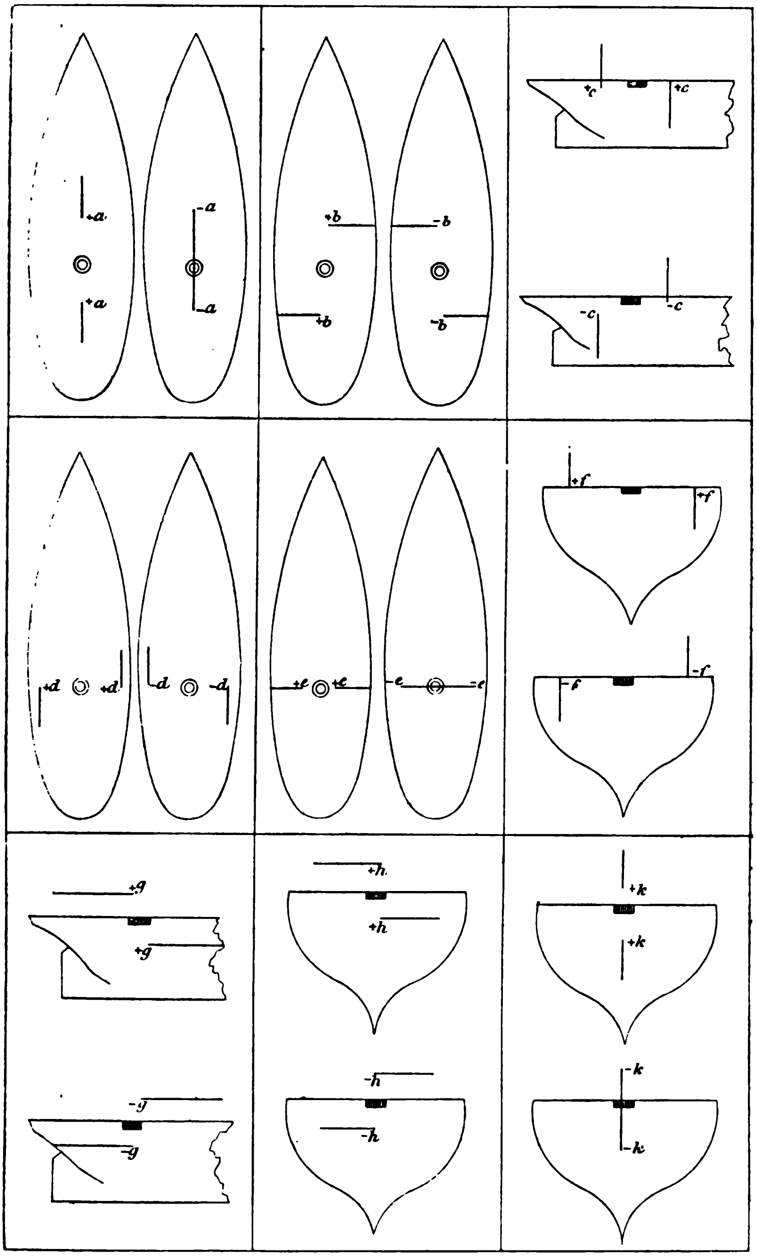


Fig. 22.

DIAGRAM SHOWING THE POSITIONS OF THE NINE SOFT IRON RODS WHICH REPRESENT THE WHOLE OF THE SOFT IRON OF A SHIP AS REGARDS ITS ACTION ON THE COMPASS.

produce 9¼° (10° × cos 23°), being now magnetised by the vertical component of the earth's total force only, such force being equal to the total force × cos (90° − dip) *see page* 33.

(3).—If the upper end retains this last position while the lower end is raised, the rod now being brought horizontal and in the magnetic meridian, the effect will be reduced to 4° (10° × cos 67°), either easterly or westerly, according to the way in which the lower end is raised, the rod being now only magnetised by the horizontal component of the earth's total force, which equals total force × cos dip.

(4).—If still keeping the original upper end fixed, the other end of the now horizontal rod is gradually turned round it as a centre, the disturbing effect on the compass lessens until, when lying East and West magnetic, it vanishes.

In any intermediate position—say, when lying N.E. and S.W.—its effect will be 2¾° (4° × cos 4 points).

A similar rod of hard iron would in all these positions produce a permanent unchanging effect if of sufficient length for us to be able to consider only the nearer pole to be acting, such length being at least fifty times its diameter. Experiments such as these are very difficult to practically carry out, as *perfectly* soft iron is almost unknown. The best results are obtained with a *long* thin rod (to avoid the action of both poles), which has been previously raised to a high temperature, and slowly cooled when lying East and West magnetic.

Change of geographical position generally involves, in the case of vertical soft iron, alterations in the deviation of a different character to those described in the last lecture as caused by hard iron, since now *both* the directive force of the compass and the disturbing power vary.

The rod *(c)*, representing the ship's vertical soft iron will, as long as the dip remains constant, behave exactly like a vertical permanent magnet with blue pole up in the northern magnetic hemisphere and red up in the southern, and if it *were* a magnet and not of soft iron would, on change of position, cause the deviation to vary *inversely* as the earth's horizontal force ($\frac{1}{H}$) in exactly the same way as a horizontal magnet does (by varying *inversely* we mean that one increases as the other diminishes and *vice versâ*), but being of soft iron and magnetised by V, the earth's vertical force, the disturbing force will, on change of position, vary *directly* as V, that is, they will increase or decrease together, the result being that the deviation will change as the two multiplied together, viz. $\frac{1}{H} \times V = \frac{V}{H}$ = tangent dip as shown in Fig. 23.

To illustrate this, suppose a vessel having in the English Channel a maximum deviation from this cause of + 10° (that is, 10° easterly with head East), to proceed to Bombay *viâ* the Cape of Good Hope.

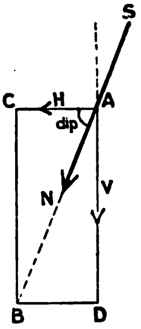


Fig. 23.

On referring to the chart of the Lines of Equal Magnetic Dip (No. 2 of the Manual or Chart 2 at the end of this book), we see that as she proceeds south in the Atlantic, since the dip, and therefore its tangent decrease, her deviation on any one point or the maximum will steadily decrease until her arrival in about latitude 10° S., when, being on the magnetic equator, it will disappear, since the dip is nothing, so that no vertical force exists to magnetise the vertical soft iron.

On proceeding further south the deviation will reappear with the opposite sign, and if she kept on until in the same southerly dip as she originally was in northerly dip in the English Channel, her deviation on East would be – 10° or 10° westerly, but on rounding the Cape her deviation will be $10° \times \frac{\text{tan dip at Cape}}{\text{tan dip in Channel}}$ or $10° \times \frac{1{\cdot}7}{2{\cdot}4} = 7°$ westerly.

On steering north in the Indian Ocean this westerly error will decrease, disappearing entirely in about 10° N., when again on the magnetic equator, while at Bombay it will be again easterly, the amount being $10° \times \frac{0{\cdot}36}{2{\cdot}4}$ or $1\frac{1}{2}°$.

Such changes as these on change of dip usually take a little time to act, and the effect, in consequence, appears to lag behind that due to a ship's *present* position.

On examining the Dip Chart we see that over the most frequented parts of the world, except off the coasts of Canada and Newfoundland, the dip, and therefore its tangent, is less than in England, and hence the deviation from vertical soft iron should be generally everywhere less, a similar observation to that already made for another reason with regard to hard iron.

The very smallest amount of vertical soft iron would produce an infinite amount of deviation at the magnetic poles, where the dip being 90° its tangent is infinity, and the north point of the compass would follow the pole of the ship as she swung round.

Here we may note that on change of position the part of the semicircular deviation caused by hard iron or permanent magnetism will vary in amount but not in sign, while that part arising from vertical soft iron will alter in amount and (on change of magnetic hemisphere) in sign also.

This, we shall presently see, often affords a ready way of distinguishing the one part from the other.

When we either know or can estimate the error produced by vertical soft iron it can be accurately corrected by placing a vertical soft iron rod on the opposite side of the compass to that from which the error proceeds, thus in Fig. 19, while compass (2) would require no such rod at all (1) would need a rod placed abaft it, and (3) one forward of it.

Such a rod (known as a "Flinders" bar) might be applied either as one of fixed length with power of regulating its distance from the compass, or more conveniently and generally, as one fixed in position but variable in length, the power varying roughly with the length.

As supplied with Thomson's compass, Flinders bar is formed of carefully prepared cylindrical soft iron 3 inches in diameter, made in pieces of various lengths (one each of 12 ins., 6, 3, 1½ and two of ¾ ins.), so that when they are all utilized they form a rod 2 ft. long, fully occupying a brass case either (as required) on the fore or after side of the binnacle, and capable of correcting on shore in the south of England 22° of deviation.

If so great effect is not required a suitable length can be made up, keeping the longer pieces on top—as they are probably more uniformly magnetised than the smaller pieces—and substituting similar wooden chocks for the lower unused portions.

The bar should always be placed with its upper magnetic pole (which is about $\frac{1}{12}$ of its length from the end) in the plane of the needles so that it might not exercise any vertical force on the compass, and when the full length of bar is employed it occupies such a position; if using any shorter length—say 12 inches—the wooden chocks must be regulated so that the top of the bar is one inch lower than before.

It will be observed that if a compass is so placed—as was formerly the case with standard compasses in the Royal Navy—that the vertical soft iron forward of it is practically equal in amount to that abaft it (as at compass (2) in Fig. 19), no Flinder's bar is required.

A compass in the midship line will always have equal amounts of vertical soft iron to starboard and to port of it which will neutralise each other, but this is by no means the case at a compass out of the midship line, such as an ordinary binnacle compass.

Table 5 of the Manual gives the action on shore of various lengths of Flinder's bar as fitted to Thomson's compass in the south of England. To adapt this to other localities we must remember the effect of a change of dip; thus 24·4 ins. of bar produces nearly 22° of effect on shore in England, where the dip is 67°, but at a place where the dip is 20°, the same length of bar would only produce an effect of 3½°, being less in proportion of tan 20° to tan 67°.

The reduction of the pointing power of a compass on board an iron ship (explained in Lecture VI.) will affect the action of Flinder's bar on board as compared with that on shore in a similar way and for a similar reason to the above, so that, if as invariably happens, the pointing power is less on board that on shore, the same length of bar will produce a greater effect.

Thus at a compass in a ship at the second position, if the directive force on board was half that on shore, 7° of effect would be produced.

As this loss of directive force is different at different compasses in even the same ship, Table 5 gives results obtained *on shore* at one place (practically applicable to the whole south coast of England), from which, if required, calculations can be made as above.

The semi-circular effects of fore and aft hard iron and vertical soft iron being indistinguishable from each other while the ship is at any one place, both might temporarily be corrected with fore and aft magnets (as on *page* 22), but on any change of dip such magnets would require re-adjusting; conversly, by making observations of deviations with head east or west in two dips, differing at least 30°, and the more the better, the two portions of semi-circular error can be separated and suitable correctors applied to each.

Thus, suppose a vessel at Plymouth with head East (compass) has 10° easterly deviation caused by the united action of unknown quantities of hard and vertical soft iron, and at Jamaica also with head East to have 4° easterly deviation.

Naturally, we should expect the deviation from both causes to be less at Jamaica than at Plymouth, since the horizontal force of the earth has increased, and the dip and its tangent decreased.

Calling, then, the unknown part of the hard iron effect at Jamaica x, and the equally unknown part of the vertical soft iron effect at that place y, we have:—

$$(1)\ x + y = + 4^\circ$$

But both hard and vertical soft iron occupied the same positions with regard to the compass at each place, on the supposition that the correctors, if any are in position, have not been moved during the voyage, only at Plymouth, as compared with Jamaica the hard iron produced an effect $= x \times \frac{\text{hor. force Jamaica}}{\text{hor. force Plymouth}} = 1{\cdot}7\,x$ and the vertical soft iron an effect $= y \times \frac{\text{tan dip Plymouth}}{\text{tan dip Jamaica}} = 2\,y$; hence from the observation at Plymouth we have:—

$$(2)\ 1{\cdot}7\,x + 2\,y = + 10^\circ$$

From equations (1) and (2) we find $x = -7^\circ$ and $y = +11^\circ$. To correct this with the ship's head placed East magnetic at Jamaica, introduce a sufficient length of Flinders bar abaft the compass to correct y or 11° of easterly error, and then correct the whole of x or the 7° of westerly error now remaining with fore and aft magnets, red poles aft; if correctors of either or both kinds are already in position they must be moved in a corresponding way.

When thus dealt with the compass should remain correct in all places, for the permanent magnetism of the ship will be everywhere annulled by the permanent magnets if accurately placed, and as the vertical soft iron of the ship changes its effect, that of the Flinders bar will equally change and everywhere produce exactly the opposite effect.

In many cases during a voyage which takes a vessel across or even near the magnetic equator, advantage might be taken of the fact that since vertical soft iron is only magnetised by the vertical force of the earth, in such positions any amount of it in a ship will produce no deviation.

If, then, on a voyage from England to Australia, *viâ* the Suez Canal, a vessel stopping at Aden is placed with her head East magnetic, and 5° easterly deviation observed, this must be solely the effect of hard iron, and should be entirely and permanently corrected by fore and aft magnets, placed red poles forward. On proceeding across the Indian Ocean and arriving, say in lat. 15° S, and dip 40°, if the ship's head is again placed East magnetic and 4° westerly deviation observed, this must be wholly caused by vertical soft iron forward of the compass (the ship being south of the magnetic equator), and should be entirely and permanently corrected by a Flinders bar abaft the compass. In either of the preceding methods of correction it is indifferent whether the observations and corrections are made with head East or West, since in either of these cases the causes of error must be both producing nearly their greatest effects.

It is advisable in the first case to wait as long as possible at the second place before correction, in order that sub-permanent magnetism might decrease or disappear.

If, as generally happens in a sea-going ship, correctors are already in position, they must be moved in the same way as though we were beginning afresh, thus, in the last case, if at Aden there are already in the binnacle fore and aft magnets, red poles forward, they will require raising, or if with red poles aft, lowering, and if later on when adjusting for vertical soft iron there is a Flinders bar already in the brass case abaft the compass, make it longer, or if forward of the compass reduce its length, always thinking first of what should be done if no correctors were in place, and then moving existing correctors so as to produce similar effects.

The Flinder's bar, to do its work properly, should be made of entirely soft iron, but although great care is taken to ensure this as far as possible, yet since it invariably contains a certain small amount of iron of the "hard" character, the bar should when possible be placed in position before the magnets, as its hard iron effect, if any, will then join on to the similiar effect due to the ship and both be subsequently removed by the magnet correction; this in practice is usually done when originally correcting a ship, a length of bar being selected adapted to the estimates formed from actual observations (such as those described) made in ships of a similar class and tabulated in Table 5 of the Manual. In a ship of an entirely new type, the length of bar to be used can only at first be roughly estimated from her design, but this is usually soon amended by observations made during the first voyage.

In a modern vessel of war it cannot always be assumed that, if for instance, a compass is placed well forward, a Flinders bar will be required on the fore side of the binnacle, for the vicinity of an armoured bulkhead might neutralize or reverse the effect of the ship as a whole.

To obviate the possibility of induction in the heel of the Flinders bar (F in Fig. 24) from the corrector magnets, two sets of holes are provided in the binnacle B for those placed fore and aft, so that by using them in pairs they can be kept lower down than if used singly; those placed athwartships have only one set of holes for their reception, since their two poles, being necessarily equidistant from the bar, one pole will exactly undo the inductive effect of the other.

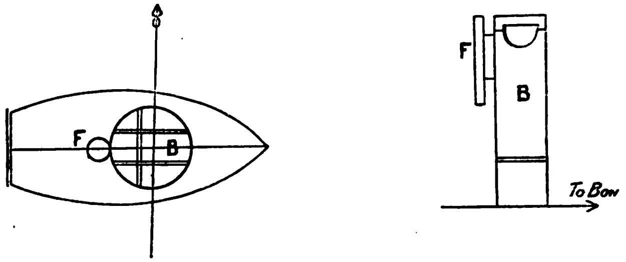


Fig. 24.

We will now draw figures representing what is generally found in practice before correction, *viz.*, a semi-circular error caused by the simultaneous action of both hard and vertical soft iron.

Suppose (Fig. 25) an iron ship to have been built in the northern hemisphere with her head N.E. magnetic, and to have a compass placed so that the vertical soft iron of the ship might be represented by a vertical soft iron rod (*c*) forward of the compass, then, on drawing the individual deviation curves, that from hard iron will be approximately represented as shown in hard line on Fig. (25 *a*), and that from vertical soft iron in the northern hemisphere by the dotted curve Fig. (25 *b*), their united effect as actually observed, being shown on Fig. (25 *c*), these figures being drawn on the supposition of the hard iron causing a maximum deviation of 10° and the vertical soft iron of 5°.

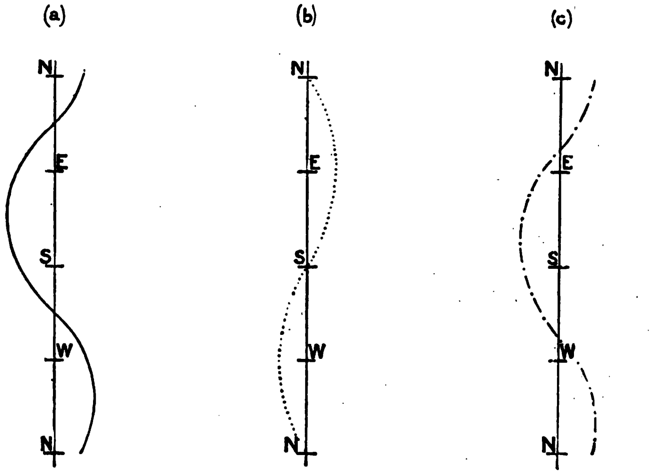


Fig. 25.

An examination of these curves shows that when we combine two semi-circular curves, we get a semi-circular curve, *i.e.*, a curve where the neutral points will still be opposite to each other, and also the maximum points at right angles to them, but such points in the resultant curve no longer correspond to those in either of the component curves, being shifted according to the predominance of one or other kinds of semi-circular error.

The combination of these two sources of error at all compasses, forms the whole of what is known as that arising from co-efficients B and C, or the whole semi-circular deviation, or $\sqrt{B^2 + C^2}$.

From the foregoing, we also see that since the effect of B on *any* course varies approximately as the sine of the angle between its nearest neutral point and that course, since the neutral points are always North or South by compass, the effect of B varies as the *sine* of the compass course; equally as the neutral points of C are at East and West by compass, its effect must vary at the sine of the angle from these points or as the *cosine* of the compass course, so that the effect of the whole semi-circular error varies as B sin co + C cos co. Thus, if B = + 10° and C = + 5°, the whole of the action of the semi-circular error on a course N. 40° E. by compass, will be approximately $10^\circ \times \sin 40^\circ + 5^\circ \times \cos 40^\circ = 6{\cdot}4^\circ + 3{\cdot}8^\circ = 10{\cdot}2^\circ$.

EXAMPLES.

1.—Given an iron rod; how would you practically ascertain whether it was "hard" or "soft"?

2.—In a ship having a vertical soft iron rod (*c*) abaft the compass, on which courses would you expect it to cause—(1) the maximum deviation; (2) the minimum deviation?

3.—If the maximum deviation in the above question (2) be 10°, draw roughly the deviation curves in (1) northerly dip and (2) equal southerly dip.

4.—Draw roughly the separate and combined curves of deviation from the following data:—

Ship built head N.W. (mag.) in northern hemisphere, vertical soft iron (*c*) forward of the compass, maximum deviation produced by each cause 10°.

5.—If the earth's horizontal force remain the same as in question 3, but the same ship be swung in the southern hemisphere where the dip is of equal amount, draw the corresponding deviation curves.

6.—If vertical soft iron causes 8° of maximum error at a compass, what deviation would you expect from this cause at (1) N.N.E.; (2) S.E.; (3) S.W. by S.; (4) W.N.W.

Ans:—3°; 6°; 4½°; 7°.

7.—A vessel at Plymouth with head West has 12° of westerly error arising from vertical soft iron; how much deviation would she probably have on N.E., S.E., S.S.W. and N.W. at (1) Quebec; (2) Aden: (3) Cape of Good Hope.

Ans:—(1) 13° E.; 13° E.; 8° W.; 13° W.
(2) Practically none.
(3) 6° W.; 6° W.; 3° E.; 6° E.

8.—A vessel at the Cape of Good Hope has 6° E. deviation with head East; this is known to be caused by 4° W. due to vertical soft iron, and 10° E. due to permanent magnetism. What would probably be the deviation on the same point at Bombay?

Ans:—6° E.

9.—A vessel leaves Plymouth with 5° E. deviation with head East, and at the Cape of Good Hope she has 15° W. deviation on the same point; what correctors should be applied?

10.—A tube suited to carry a Flinders bar is fitted to all standard binnacles. Describe how the length and position of the bar may be determined so as to correct that part of the semicircular deviation on the East and West points due to vertical induction in vertical soft iron.

11.—If observations of the deviation on the East point of the compass are taken in England and on the magnetic equator, it may be found convenient to place a Flinders bar (if required) at the latter position of the ship.

As the Flinders bar when so placed should be non-magnetic, how may the required length of bar be ascertained?

LECTURE IV.

Quadrantal Error—Symmetrical Horizontal Soft Iron—Correction by Spheres —Unsymmetrical Soft Iron—Correction of D and E combined.

The principal, and generally the only, part of quadrantal deviation which we will first consider in this lecture is the effect of the magnetic action of horizontal soft iron chiefly represented by beams, iron decks, and the horizontal part of the magnetic force induced by the earth in armour plates *(see page 27.)* At a compass placed in the midship line these forces may be considered to be symmetrically distributed round it, so that we may classify them as arising from (1) fore and aft and (2) athwartships horizontal soft iron.

The disturbing effect of cause (1) will chiefly depend upon the position of the compass with regard to it, thus in Fig. 26 such iron may be typically represented by a rod *(a)* either

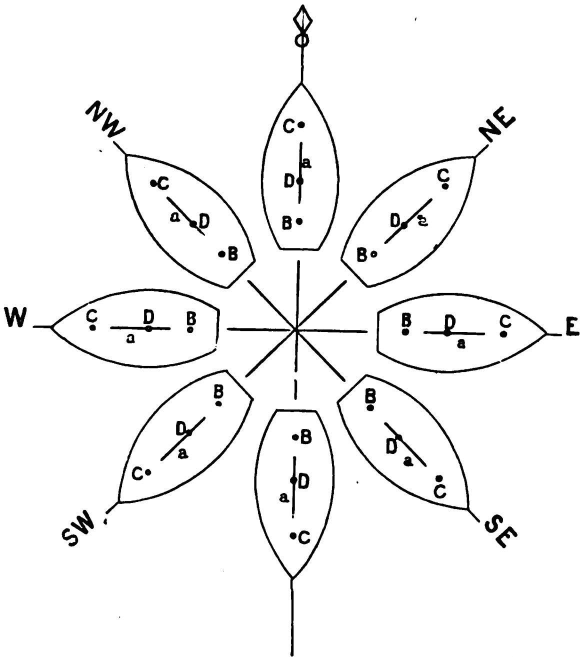


Fig. 26.

passing through a compass placed at D, or lying forward or abaft compasses placed at either B or C. In studying the disturbing effect of such a rod on each compass as the ship turns in azimuth, we must remember that we are dealing with iron magnetised only by the horizontal induction of the earth, so that when the rod lies East and West magnetic it is not magnetised at all, and in every other position the end nearest north becomes red and that nearest south blue, so that the effect in disturbing the compass will depend both on the amount of magnetism induced in the rod and the angle at which it is presented to the compass which, presumably, has very short needles, and may be regarded as a north seeking particle.

Remembering these points and drawing curves to represent the deviations as the ship is swung round, we find that at North, South, East or West (magnetic or compass), no deviation occurs at either compass, but at approximately N.E. and S.W. compass D will have westerly, and B and C easterly deviations (Fig. 27 *a*), and (27 *b*), while at N.W. and S.E. (compass) D will experience easterly, B and C will have westerly deviations.

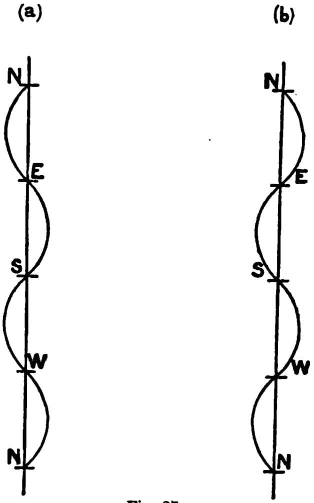


Fig. 27.

In the case of the athwartship part of the symmetrical horizontal soft iron, experience shows that wherever a compass is placed in any ship, such iron may be represented by a rod *(e)* supposed to pass through the compass and never lying on one or both sides of it (Fig. 28).

In tracing, by graphical means, the changes produced by such a rod, on swinging completely round we find a curve similar to that caused by a fore and aft rod forward or abaft the compass (Fig. 27 *b*), and the reverse of that caused by such a rod if passing through the compass (Fig. 27 *a*). In actual practice both rods *(a)* and *(e)* may be supposed to disturb all compasses on board iron ships (*see* Fig. 45, *page* 66), but in practically every case the athwartship component *(e)* is the more powerful and either acts with fore and aft iron lying either forward or abaft the compass or more frequently overpowers such iron passing through the compass (*see* Table 6 of Manual).

The result in the cases considered has been to give deviation curves having four symmetrical loops, appropriately called "quadrantal" curves, and from them we see that on opposite

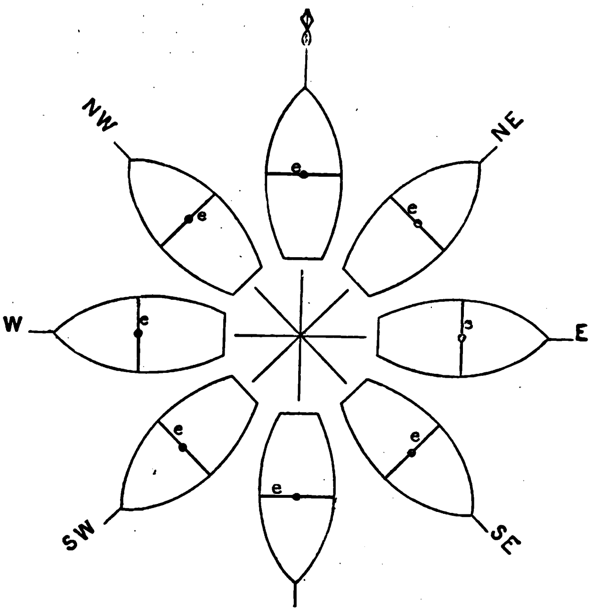


Fig. 28.

points of the compass any kind of quadrantal error causes equal amounts of deviation of the *same* sign, while, as we have already observed, any kind of semi-circular error under such circumstances causes equal amounts of error of *opposite* signs.

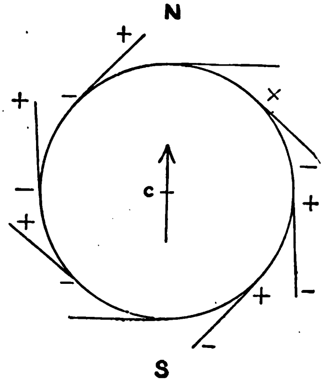


Fig. 29.

The changing magnetic character of a thin rod of horizontal soft iron, and its varying effects in disturbing a compass, is also well shown by supposing the rod to move round the compass in a circle so that one end is at a fixed distance from the centre, and its length is always a tangent to the circle (Fig. 29); the polarities of the two ends being shown as + and −, we see results similar to those before described, and also that two similar rods opposite to each other double the effect of one.

The points of no deviation in the curves we have drawn will be at N., S., E. and W. compass or magnetic, but the points on which the greatest quadrantal error occurs will not be *exactly* at N.E., S.E., S.W. and N.W., either compass or magnetic, but midway between them as, owing to deviation, the needle will not be pointing to north when the maximum effect occurs. Thus, with a quadrantal error of + 10°, the maximum effect will be found at N 40° E. by compass.

Quadrantal error arising from symmetrical soft iron is technically said to be caused by co-efficient D.

In comparing such quadrantal and semi-circular curves we must observe that the shape of the former is not dependent upon the direction of the ship's head when building, but will have its neutral points on the cardinal points if the disturbing forces are symmetrical, and the maximum points nearly 45° from these, such maximum points being termed "quadrantal" points.

In semicircular curves the form depends upon (1) the direction of the ship's head when building, and (2) the position of the vertical soft iron with regard to the compass. The neutral points and maximum points will be 90° apart, as measured by disturbed compass.

In both cases regular curves are only produced when the compass needles (as in Thomson's compass) are so short or disturbing iron so far off that we need not consider any magnetic action as affecting both poles. If this important condition is not fulfilled, horizontal soft iron will give a curve having eight loops (octantal error, Fig. 30 *a*), and hard and vertical soft iron will give curves having six loops (sextantal error, Fig. 30 *b*), both of which it is practically impossible to correct, though their effects are

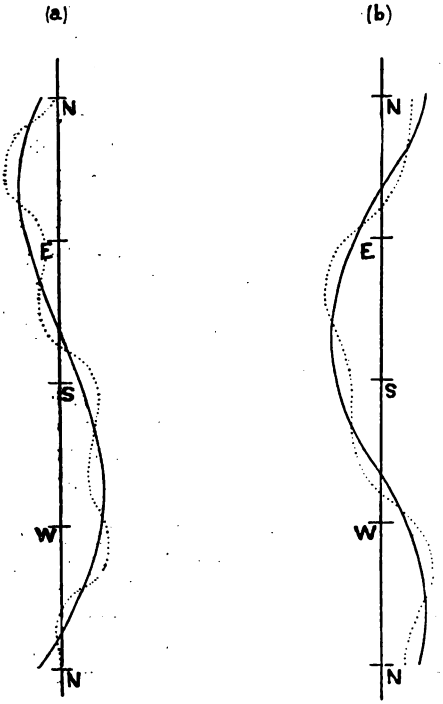


Fig. 30.

much lessened by using compasses having 2, 4, or 8 needles, suitably placed with regard to each other *(see page* 3).

In quadrantal curves the deviations on different points are connected by the approximate law, viz., that the deviation on any point equals the maximum deviation multiplied by the sine of *twice* the angle from the nearest neutral point.

Thus, at a compass, if the maximum of this kind of deviation we are considering be 10°, the amount acting at N.N.E. will be approximately 7° (10° × sine 4 pts.).

In semi-circular curves it will be remembered that the deviation varies as the sine of the *angle* from the nearest neutral point. The reason for the difference being that in the latter case the disturbing cause is permanent or equally powerful in itself on all points, but in the former it is variable, depending upon the position of the disturbing cause with regard to the magnetic meridian. As in the case of the vertical soft iron, the rod (c) which represented it was purely imaginary, having no thickness, so these rods (a) and (e) must be similarly thought of, and as again opposite effects will be produced by them in different positions, we agree to call such as may be supposed to pass through a compass minus (—), and those on one or both sides plus (+), observing that while rod e is practically — to all compasses, rod a may be + to one compass and — to another, depending on where such compasses are placed; in technical language we may say that the effect of coefficient D is caused by the united action of rods a and e, that is, either by $-e$ and $+a$ acting together, or more usually $-e$ overpowering $-a$ (*see* Table 6 of the Manual).

A curious feature of quadrantal deviation is its constancy in every part of the world, caused by the fact that the pointing power of the compass and the disturbing power of the horizontal soft iron both equally depend upon the horizontal magnetic force of the earth, and therefore, on change of position both vary in the same ratio. Thus, if we find on any particular point a quadrantal deviation of 5° E. in England, on proceeding to Bombay, where the earth's horizontal force is doubled, we still get 5° error on the same point, since, though the soft iron is magnetised twice as powerfully as before, the compass is pointing twice as strongly.

The correction of co-efficient D is a practical application of these two facts, (1) that a horizontal soft iron rod lying on one side of a compass produces an opposite effect to that of one supposed to pass through it, and (2) that in most uncorrected ships the quadrantal deviation at a compass in the midship line is of such a nature as may be represented by a soft iron rod passing through it ($-e$).

The first fact we have already experimentally tested, and the second may be shown by taking the deviation table of an uncorrected ship and examining it as follows:—Suppose the deviation on the quadrantal points to be:—N.E. + 17°; S.E. + 15°; S.W. − 10°; N.W. − 22°. That at N.E. (+ 17°) is caused by a certain amount of semi-circular error, arising probably from both hard and vertical soft iron, whose united effect we will call ± S, and the whole of the quadrantal error or co-efficient D; similarly, the deviation at S.W. (−10°) is caused by an equal amount of semi-circular error, but of the *opposite* sign to that at N.E. and therefore ∓ S, since we have gone to the opposite point of the compass, and an equal amount of quadrantal error which is of the *same* sign as that at N.E. (since this is a distinguishing feature of such deviation), so that by taking the algebraical mean of the two observed deviations (+ 17° and −10°) we get rid of the semi-circular effect, the 3½° remaining being the value of D and always found to have a positive sign (+). By similarly dealing with the deviations at N.W. and S.E. we eliminate the semi-circular effect as before, getting as a result − 3½°, which is also entirely quadrantal, being again the numerical value of D, but having the opposite sign to what it had before.

At all uncorrected compasses in all ships we get similar results to this, which would be such as that produced by either rod − *e* or rod + *a*; when, in addition to ascertaining the value of co-efficient D, we also obtain that of the mean directive force at the compass (*see* Lecture VI.), we can ascertain exactly which rods are acting with the results shown in Table 6 of the Manual, from which we see that the effects observed almost always result from the action of − *e* overpowering that of − *a*.

Although in practice quadrantal deviation is generally corrected from the result of preliminary calculations (as explained later on) and not by experiment, we may illustrate the principle of such correction by supposing an uncorrected ship in which symmetrical horizontal soft iron is the sole cause of disturbance, placed with her head N.E. magnetic and 5° of easterly deviation observed (Fig. 31), which we can assume is caused by red magnetism at the end of rod − *e* farthest from the compass; if on the port side of the compass we place a soft iron rod, *l*, the blue magnetism induced by the earth at its nearer end will obviously produce an opposite effect to the red of rod − *e*, or if we place *l* in a similar position on the starboard side its nearer red end will now produce exactly the *same* effect as when the rod was on the port side, so that two similar and similarly placed rods, one to starboard and the other to port, will double the effect of one only, and they will not as at first glance appears probable, counteract each other. One such rod is theoretically all that is required to correct D, but even if sufficiently long and powerful to do so, it would have to be so closely approached to the compass that the action on both poles would come into play, thus introducing octantal error of a far worse character than the quadrantal deviation we are trying to correct, moreover, even in compasses purposely made of weak magnetic power, the induction in this case of the compass needles on the near end of the rod would complicate the inductive force of the earth, which is the only power we want to utilise; from this we see that quadrantal correction is very difficult to effect with compasses having long needles.

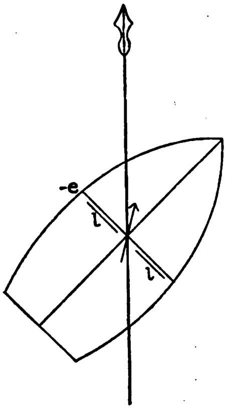


Fig. 31.

Originally, correctors in the form of rods, boxes of iron chain, or scrolls of soft iron were employed, but more recently, hollow, soft iron spheres supported on brass brackets have conveniently taken their place, as they are more regular in effects.

A hollow sphere, if its thickness exceeds one-tenth of its diameter, produces the same magnetic effects as if solid throughout, the magnetic properties of the internal portions removed neutralising one another.

It must be remembered that in the most usual case of the distribution of horizontal soft iron in a ship it is the *excess* of the action of rod $-e$ over that of rod $-a$ we are correcting, since equal rods $-e$ and $-a$ produce no deviation.

If, however, the quadrantal error we are considering be produced (as occasionally happens) by $-e$ and $+a$ acting together, the position for the corrector spheres will still be athwartships, and they now will correct the *united* effects of e and a.

As e is invariably $-$, a $-$ D could only be produced by the action of $-e$ and $-a$, the latter being the greater, which it never is; theoretically a $-$ D would necessitate the corrector spheres being placed fore and aft.

If $-$ D is found *after correction*, it shows that the spheres are too close, and *vice versâ* if $+$ D exists.

It will be instructive now to see the form of deviation curve which results from the united action of semicircular deviation and quadrantal of the kind considered (D).

On referring to Fig. 25 c we saw there the united effect of the two semi-circular curves for a certain ship, so that we must for the same vessel (on the supposition that she has a quadrantal deviation of 5°) combine the dotted curve on Fig. (32 *a*) with that shown in hard line, remembering that, although in another ship —or at another compass in the same ship—this semicircular curve might be entirely different in form, yet the quadrantal curve is always of similar form.

The resulting curve shown on Fig. (32 *b*) is neither semicircular nor quadrantal, and is capable of assuming an almost infinite variety of forms consistent with the condition (at compasses in the midship line) of the sum of the easterly deviations equalling that of those westerly.

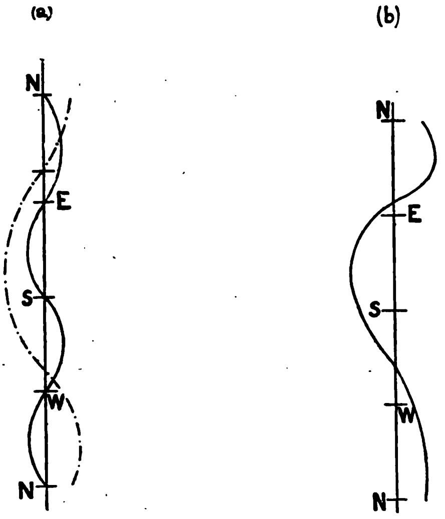


Fig. 32.

Besides the action of symmetrical horizontal soft iron in producing quadrantal deviation of the kind known as co-efficient D, we have, at compasses out of the midship line, to consider the additional quadrantal error produced by similar *un*symmetrical iron.

The general effect of this, when acting alone, may be illustrated (Fig. 33), by supposing such disturbing causes to be represented by a horizontal soft iron rod (*t*), pointing to the compass A, and lying in its plane at any angle on either bow or quarter, or on both. Such a rod, as the ship turns round will, for the same reason as shown on Fig. 26, cause quadrantal error, since any such rod or rods, being of soft iron, will produce no deviation when, owing to the movement of the ship, they lie (1) in a line with the compass needles, or (2) magnetic East or West, and will cause their greatest disturbance between these points, thus, on swinging completely round, giving four points of no deviation and four points of equal maximum error; if the angle with the fore and aft line at which such rod or rods lie is 45°, such error will attain a maximum value approximately on the

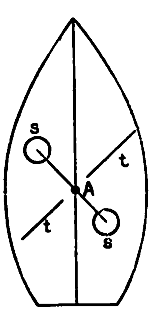


Fig. 33.

cardinal points, and have no value on the quadrantal points, thus differing from the effect of symmetrical iron of this character (D), whose maxima and minima points are oppositely situated to these.

The effect in this case is technically said to arise from the action of co-efficient E, and (Fig. 34 *a*) shows the form of curve caused by + E as developed at a port binnacle compass, while Fig. (34 *b*) shows the curve caused by − E as would occur at a starboard binnacle compass. The diagonally placed rod, such as we have been considering, is more correctly represented by two equal and unsymmetrical rods (*d*), lying fore and aft, and (*b*), athwartships (*see* Fig. 22). The correction of this part of quadrantal error if acting alone would be effected by soft iron rods or spheres (*s s*), placed at an angle of 45° with the fore and aft line, and at right angles to that causing E, thus in Fig. 33 + E would require correctors placed in a line from the port bow to the starboard quarter, and − E correctors at right angles to these.

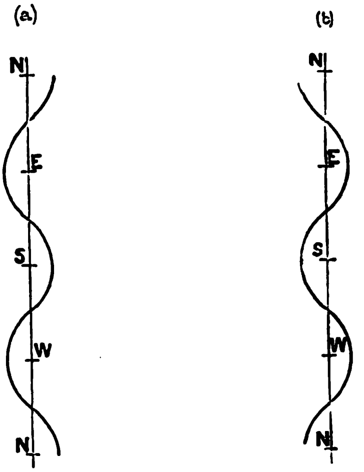


Fig. 34.

The spheres for this purpose are mounted on a moveable cradle, which can be rotated through any desired angle.

When both co-efficients, D and E, are acting, the total quadrantal curve observed will be that formed by their united action; thus, if $D = + 8°$ and $E = - 3°$, the former will give rise to a curve such as that on Fig. (35 *a*), and the latter will be represented by Fig. (35 *b*), their united effect, or that shown on Fig. (35 *c*), being such as would arise from the action of one soft iron rod pointing to the centre of the compass and lying at an angle of 10° with the fore and aft line from port bow to starboard quarter, and at such a distance as to be capable of producing 8½° of error $(\sqrt{D^2 + E^2})$, *see page* 58.

It would be difficult to experimentally correct a compass for both D and E, for if we placed the ship on a quadrantal point where E is not acting, and put on spheres athwartships to correct D, then, on placing the ship's head on a cardinal point where D is not acting, and moving the spheres out of the athwartships position to correct E, we should disturb the

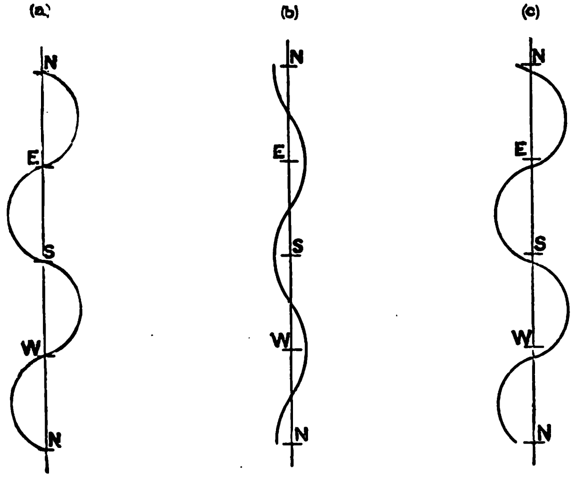


Fig. 35.

original adjustment of D, and similarly, if we began with the correction of E, and then proceeded to that of D.

It is therefore customary to correct both parts of the quadrantal error at the same time by calculation, the maximum value of the united effects of D and E being $\sqrt{D^2 + E^2}$ which, on reference to Table 4 of the Manual, will determine the size of the spheres required and their distance from the compass, while the angle with the athwartships line, through which the spheres must be rotated, is found by halving the angle whose tangent is $\frac{E}{D}$. Thus, in the preceding case, spheres of 12 ins. diameter would be required, placed 9·5 ins. from the centre of the compass to their nearest points, and at an angle of 10° with the athwartships line, the starboard sphere moving forward. The spheres will always be finally secured in some position between athwartships and four points before or abaft the beam, according as E is + or —, in the first case the port sphere moving forwards and *vice versâ*.

This arises from the fact that E alone would necessitate placing the spheres in a line at 45° on either bow or quarter, but as D always exists as well as E and is always +, the correction of this also will bring the line of spheres nearer to the midship line than if they were used for correcting E alone.

In the theoretical case of a compass having — D (caused by — a being more powerful than — e, or by + e acting with — a, or overpowering + a), the spheres would be placed fore and aft; if, moreover, E was also acting, they would have to be rotated into some position between the fore and aft line and a line from four points on either bow to 45° on either quarter.

The action of a soft iron sphere as a quadrantal corrector is best understood when we think of it as a temporary magnet (produced by the induction of the earth) pivotted in such a way that its centre is in the plane of the compass needles and that it always points in the magnetic meridian and also in the line of dip, regardless of the varying direction of the ship's head.

Such a temporary magnet is equivalent to two of the same length as the diameter of the sphere, one horizontal and the other vertical; the effect of the former, when carried round a compass having very short needles, if kept at the same distance, measured from centre to centre and always pointing in the same direction, will be found to cause quadrantal error; thus, in Fig. 36, such a magnet will produce no error on the compass C when either N., S., E. or W. of it, but when N.E. and S.W. of it will cause easterly error, and when N.W. and S.E. of it, westerly error, so that its effect is quadrantal.

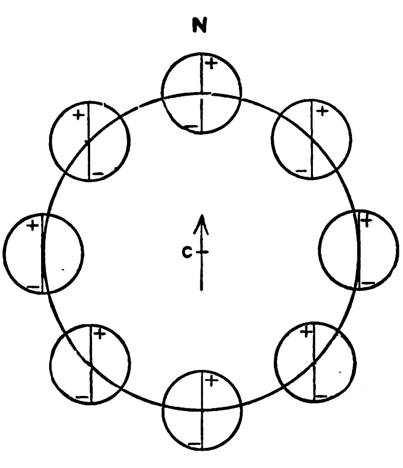


Fig. 36.

Two spheres, as we have seen, double the effect of one, and, of course, whatever by itself would *cause* quadrantal error can be used to *correct* such error if already existing.

We may note that a *permanent* horizontal magnet similarly carried round a compass would also at any one place cause similar quadrantal error.

Such temporary magnets, as the spheres become, will, as we have seen, exercise both a horizontal force (which is what is utilised for quadrantal correction), and also a vertical force which, when the ship heels, is useful in correcting one part of the heeling error *(see page* 85*)*.

The power of this temporary vertical magnet remains constant in the same dip.

As spheres of various sizes, according to requirement, are supplied with Thomson's compass, the lengths of their stands or supports are varied, so that the centres of each pair of spheres, whether large or small, are always in the plane of the needles, and, to obviate their action on both poles of the compass, they must not be approached within a distance of twice the length of the longest needle, measured from the centre of the compass to their nearest parts.

The reduction in the pointing power of a compass on board an iron ship (explained in Lecture VI) will not affect the action of the corrector spheres on board as compared with that action on shore, since, being of soft iron, they and the compass are equally acted on by the modification of the earth's horizontal force on board.

Thus, if on shore, when placed in a certain direction from the centre of the compass, and at a certain distance from it, 5° of deviation are produced, the same result will be found, under similar conditions, anywhere in any ship.

Finally, we may note that horizontal soft-iron rods acting separately produce quadrantal effects only, but acting in certain combinations they produce constant errors also *(see page 56)*.

A magnet and a vertical soft iron rod always present the same poles to the compass as a ship turns round, but a horizontal rod of soft iron presents its two poles alternately.

From the above, we see that the action of D on *any* point is, approximately, equal to D multiplied by the sine of twice the angle from its nearest neutral point, or sine twice the compass course, and similarly with regard to E, whose neutral points being the quadrantral points, the sine of twice such angle is the same as the *cosine* of twice the compass course, so that on any point the whole quadrantal effect = D sin 2 Co. + E cos. 2 Co.

Thus, if D = + 8° and E = + 5°, the total quadrantal deviation on a N. 30° E. compass course will be 8° × sin 60° + 5° × cos. 60° = 7° + 2½° = 9½°.

EXAMPLES.

1.—Why does a soft-iron rod in a vertical position give semicircular error, and in a horizontal position quadrantal error?

2.—If co-efficient D has a value of + 5°, what will be the amount and sign of the deviation at (1) N.N.E.; (2) S.E.; (3) S.S.W.; (4) W.N.W.?

Answer:—3½° E.; 5° W.; 3½° E.; 3½° W.

3.—A wooden ship having a Thomson compass is placed with head N.E. and a pair of spheres shipped; what kind of deviation will they produce?

4.—In a ship swung at Devonport, where the standard compass was corrected by spheres, the resulting quadrantal deviation was — 1°. What would be the probable quadrantal deviation at Singapore for the same compass, spheres not moved?

Earth's horizontal force, Devonport = 1·0.
„ „ „ Singapore = 2·0.

5.—How does deviation change when a ship changes her magnetic latitude, if due to—(*a*) hard iron; (*b*) vertical soft iron; (*c*) horizontal soft iron?

6.—A ship built with her head N.E. (mag.) has vertical soft iron represented by a rod before the compass, and horizontal soft iron represented by an athwartships rod below the compass; the maximum deviation from each cause being 10°, what will her deviations at the same place (in the northern hemisphere) be with head North, N.E., East, and S.E.?

Answer:—7° E.; 17° E.; 3° E.; 13° W.

7.—An iron ship was built with head S.E. (mag.), and had a vertical soft-iron rod (*c*) before the compass, and a horizontal soft-iron rod ($-e$) under the compass. Supposing that she had a maximum amount of deviation of 10° from each of these causes, what would be her total deviation if uncorrected, with her head at N., N.E., and N.W., (*a*) at Plymouth; (*b*) at Cape Horn?

Answer:—*(a)* 7° E.; 27° E.; 17° W.
(b) 4½° E.; 13½° E.; 6½° W.

8.—Draw roughly the individual and combined deviation curves in question 6, and at Cape Horn in question 7?

9.—Co-efficient E being + 4°, what deviation from this cause will there be at (1) N.N.E.; (2) E.S.E.; (3) S.W.; (4) W.N.W.

Answer:—3° E.; 3° W.; 0; 3° W.

10.—If $D = +10°$ and $E = -6°$, draw the individual and combined quadrantal curves?

How would you correct the compass for these combined errors?

LECTURE V.

The Coefficients—Practical Representation—Analysis of Deviation Table—Individual Curves arising from each Co-efficient.

When our object is to only correct the errors of a compass while the ship is upright, the mechanical operations of adjustment can, as we have seen, be generally performed experimentally and without calculation, as, indeed, is the usual practice in the Mercantile Marine; but this is not so with regard to the correction of the heeling error, especially when it attains such large values as we find in vessels of war. Moreover, experience shows that the ordinary correction for quadrantal error is best made from preliminary calculations, and besides this, a continuous record of the magnetic condition of a ship, expressed in the form of what are known as "co-efficients," is valuable, both as a means of tracing magnetic changes occurring with lapse of time, and, in sea-going ships, affording a simple means of testing the accuracy of a deviation table.

The fundamental equation on which both the theory and practice of compass adjustment are based is as follows :—

(1) Sin dev. = A cos. dev. + B sin Co. + C cos. Co. + D sin (2 Co. + dev.) + E cos. (2 Co. + dev.).

This equation, where A, B, C, D and E are constant quantities termed "co-efficients," and Co. is the compass direction of the ship's head, expresses the disturbance, or deviation, however great—or rather the sine of such disturbance in degrees—occasioned by the action of any possible arrangement of hard or soft iron, whether vertical or horizontal, on board an iron ship when upright. This is on the supposition that such causes act in the plane of the compass, and that the needles have no appreciable length, conditions very approximately fulfilled in well-placed modern compasses, so that this formula, originally due to investigations of mathematicians, has, after prolonged tests, become that on which all practical work is based.

From the original equation we see :—

(1) That if the values of A, B, C, D and E are known, we might, for a given course, calculate the deviation, or

(2) If the deviation be observed on five selected compass courses, the values of the unknown co-efficients can be found by ordinary algebraical methods, as five equations will be so formed. Thus, if with the ship's head N.E. by compass, 32° of easterly deviation are found, we have by substitution

$$\sin 32^\circ = A \cos. 32^\circ + B \sin 45^\circ + C \cos. 45^\circ$$
$$+ D \sin 122^\circ + E. \cos. 122^\circ$$

and so on, for other points on which the deviation has been observed.

The first of these operations (1) is, in practice, very rarely needed, as it is generally both more simple and accurate to *observe* the deviation when required; but in originally correcting a compass, the values of the co-efficients are always obtained by the second process (2) from the results of careful swinging without any correctors in place, and as the accuracy of these values will be increased by using a greater number of equations than the five which are all that are absolutely necessary, it is usual, in important ships, to form them for the eight principal compass points of each of the chief compasses on board, or in those cases (such as many standard compasses) where there is good reason to suppose that A and E do not exist, observations made on any two adjacent cardinal points and the intermediate quadrantal point will suffice for calculating B, C and D, since only as many equations are needed as there are unknown quantities to find.

When the values of A, B, C, D and E are obtained from the accurate expression given above, they are termed "exact" co-efficients, and are expressed in the Manual in German characters, and in terms of the mean directive force on board taken as unity *(see page* 67*)*, so, that being only parts of that force, they are always less than unity; thus, if the exact co-efficient B for a particular compass is ·4, this means that the total fore and aft magnetic force of the ship, caused, as we have seen *(page* 35*)*, partly by permanent magnetism and partly by vertical soft iron, is $\frac{4}{10}$ of the mean force with which on board the compass is pointing.

When the maximum deviation from all causes does not exceed 20°—which is the case in many ordinary ships and in all vessels when ready for sea—the original equation can be expressed in this more simple form:—

(2). Dev. in degrees = A + B sin Co. + C cos. Co. + D sine 2 Co. + E cos. 2 Co. which differs from the original and exact equation by considering the sine of the deviation equal to the deviation itself, that cos. dev. = 1, and that the sine and cos. of (2 Co. + dev.) are equivalent to the sine and cos. of 2 Co. alone. These suppositions would be inadmissible with such large angles as we should introduce into the fundamental equation if the deviation exceeded 20°.

Finally, when A and E do not exist, equation (2) can be still more simply expressed as:—

(3). Dev. in degrees = B sin Co. + C cos. Co. + D sin 2 Co. When the values of A, B, C, D and E are found from either equations (2) or (3), they are termed "approximate" co-efficients, and are expressed in degrees.

The co-efficients mean the same thing however obtained, and are only termed exact or approximate according to the more or less exact equations from which they are found; in all cases, they, as we shall see, can be represented by the actions of certain magnets and soft iron rods, whose combined effects represent the whole magnetic action of the ship.

The exact co-efficients, when the deviation is less than 20°, are approximately the natural sines of the approximate co-efficients, or in other words, the fraction of the mean pointing power on board, which each exact co-efficient represents, is capable of producing when it is most efficiently placed with regard to the compass, a deviation equal to that represented by the corresponding approximate co-efficient.

To illustrate first the simplest, and therefore least accurate way of finding, in a given case, the values of the approximate co-efficients, suppose, in an uncorrected ship, the deviations on the four cardinal points to be as follows:—

North, 2° E.; East, 11° E.; South, 12° E.; West, 9° W.

If we consider easterly deviation plus, and westerly minus, and measure the compass course through 360°, being 0° at North, 90° at East, 180° at South, and 270° at West, we find on substitution in equation (2).

$$\begin{array}{lrcl}
\text{At North} & +\ 2^\circ & = & A + B\sin\ 0^\circ + C\cos.\ 0^\circ + D\sin\ 0^\circ + E\cos.\ 0^\circ \\
\text{,, East} & +\ 11 & = & A + B\sin\ 90 + C\cos.\ 90 + D\sin\ 180 + E\cos.\ 180 \\
\text{,, South} & +\ 12 & = & A + B\sin\ 180 + C\cos.\ 180 + D\sin\ 360 + E\cos.\ 360 \\
\text{,, West} & -\ 9 & = & A + B\sin\ 270 + C\cos.\ 270 + D\sin\ 540 + E\cos.\ 540
\end{array}$$

Which become, when we give the proper value to these sines and cosines

$$\begin{array}{rcl}
+\ 2^\circ & = & A + 0 + C + 0 + E. \\
+\ 11 & = & A + B + 0 + 0 - E. \\
+\ 12 & = & A - 0 - C + 0 + E. \\
-\ 9 & = & A - B + 0 + 0 - E.
\end{array}$$

On adding each side algebraically and dividing by 4, we get $A = +\ 4^\circ$. Now, since this 4° is not multiplied by either the sine or cosine of the course, it must have the same constant value on *all* courses, and if we think of what is capable of producing such an effect, we see from former lectures that it cannot be caused by either hard iron, vertical soft iron, or symmetrical horizontal soft iron, since these produce semi-circular and quadrantal, but not constant, effects. If, however, we suppose a

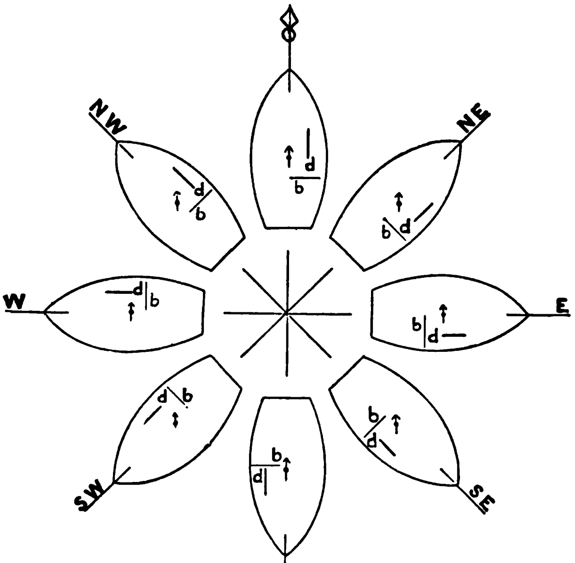


Fig 37.

compass, such as a port binnacle compass, to be acted on by unsymmetrical horizontal soft iron of such a character as may be represented by two equal rods, one (*d*) fore and aft on the starboard and forward side of the compass, and (*b*) athwartships and also on the starboard side abaft it (Fig. 37), and if each of these rods, when placed by the movement of the ship so as to act most efficiently on the compass, can give 4° of easterly error, we see on studying Fig. 37 that this combined effect will give this same error of 4° on *every* point, while a similar arrangement of soft iron rods on the port side, acting on the starboard binnacle compass, would on all points cause an equal, but opposite effect.

The former effect is termed + A and the latter – A, and its value from any deviation table may, evidently, be equally well determined by taking the algebraical mean of the deviations observed on *any* four equi-distant compass points, or, best of all, by doing so with all the equi-distant points on which the ship has been swung.

Co-efficient A being the result of unsymmetrical iron should have no value at a standard compass placed in the midship line, and if, in such a case, on thus testing a deviation table a sensible value (over ½°) is found, it may usually be attributed to swinging with a wrong bearing *(see page* 23.*)* At a binnacle compass, when out of the midship line, A often attains a considerable value and is usually one principal cause, in sea-going ships, of discrepancies between the direction of a ship's head as shown by standard and steering compasses.

When A exists at a compass, its effect, as far as shaping a course is concerned, may be entirely obviated by shifting the lubber line, remembering that doing so will have no influence on the constant error introduced by this co-efficient when using the compass for taking bearings, which error would always have to be allowed for and is never corrected, as doing so would involve moving the compass needles so that the imaginary magnetic axis which represents them was no longer coincident with the north and south line of the card.

Thus, if at a compass corrected for all other errors, there remains an A = + 4° when the ship's head is North by compass, it is really N. 4° E. magnetic, so that the lubber line must be shifted 4° to starboard to make the two agree.

A, being caused by horizontal soft iron will, in all parts of the world, produce the same error for a similar reason to that which causes quadrantal error to be everywhere the same.

From the foregoing we see that since A is the effect of unsymmetrical horizontal soft iron, we could, theoretically, at any *one* place determine the value of the vertical soft iron part of the semicircular error *(c)*, if we compared the values of A found on swinging the ship both upright and heeled over, since the symmetrical vertical position of this rod in the former case becomes unsymmetrical and partly horizontal in the latter case, and similarly with regard to fore and aft horizontal soft iron (*g* of Fig. 22), which, when upright, is symmetrically above or below the compass, but is not so when heeled over.

In practice, however, it is found very difficult to do this.

On again referring to equation (2) we see that by changing signs on both sides of that expressing the deviation at West and adding to it that found with head East, we get rid of the values of A and E and find that 2 B = 20°, and therefore B (which represents the total fore and aft magnetic pull on the compass) = + 10°. This, we have already seen, will be corrected by either fore and aft magnets—red poles forward—alone, or more usually by a combination of these and Flinder's bar, according to experience in similar ships or judgment in one of a new type.

By similarly dealing with the deviation at North and South (that is, reversing the sign of that at South and then taking the mean of the two), we get rid of the effects of A and E and obtain the value of C = – 5°.

This represents the athwartships magnetic pull on the compass, and is always corrected at all compasses by athwartships magnets (in this case having red poles to port).

At a compass in the midship line this is both theoretically and practically correct, but at a compass out of this line there should be applied, in addition to magnets, a vertical soft iron rod to port or to starboard to correct the excess of similar iron in the ship on one side over the other (shown as *f* on Fig. 22).

As this is not done in practice, unless, as a rule, the athwartship's magnets at a binnacle compass are occasionally moved on change of dip, discrepancies will be found between the indications of such a compass and the standard.

It will be noticed that when an A and E exist, the deviations observed at East and West often differ from one another considerably, and similarly those at North and South, but where there is neither A nor E these deviations on opposite points will (if not greater than 20°), practically agree, and will each represent the numerical values of B and C, but will have opposite signs on opposite points.

It will also be remarked that, when correcting B and C, the values of the united effects of A and E should be left in on the cardinal points unless they have been, wholly or partially, previously corrected, since these co-efficients cannot be corrected by magnets.

To find the value of D, or that part of the quadrantal deviation caused by symmetrical horizontal soft iron, since this has no effect on the cardinal points, we must proceed as on page 45, or use those equations formed by substituting in equation (2) on page 54, the values of the deviations observed on the quadrantal points, thus, if in the same ship these are N.E. $+ 15\frac{1}{2}^\circ$, S.E. $+ 6\frac{1}{2}^\circ$, S.W. $+ 8\frac{1}{2}^\circ$, and N.W. $- 14\frac{1}{2}^\circ$, we then get:—

$$\begin{array}{ll}
(1) & + 15\frac{1}{2}^\circ = A + B_1 + C_1 + D + 0. \\
(2) & + 6\frac{1}{2}^\circ = A + B_2 + C_2 - D + 0. \\
(3) & + 8\frac{1}{2}^\circ = A - B_1 - C_1 + D + 0. \\
(4) & - 14\frac{1}{2}^\circ = A - B_2 - C_2 - D + 0.
\end{array}$$

Where B B_2 and C C_2 are the parts of B and C (if not previously corrected) acting on the quadrantal points, and which, from their semicircular character, will be equal in amount but have opposite signs on opposite points; the amounts in this case being B sin 45° = 7° and C cos. 45° = $- 3\frac{1}{2}^\circ$.

By changing signs on both sides of equations (2) and (4) and then adding all four equations together we get rid of everything except D, finding that 32° = 4 D and, therefore, D = + 8°.

If no A existed the numerical value of D would be found by meaning *either* the deviations at N.E. and S.W. or those at N.W. and S.E., but, obviously, these would differ in sign. If, however, A exists, such means give the value of A ± D, and therefore D would have to be found by ascertaining A first and allowing for it.

D, as we have already seen, if it exists without E, is corrected by spheres placed athwartships and having their centres in the plane of the needles.

To find the value of E from equation (2) on page 54, we see that by applying a similar method to that by which A was determined, if we add together the deviations at North and South as observed, and to this sum add that of the deviation at East and West, having previously changed signs on both sides of these, we get rid of A, B and C, and find 12° = 4 E, and therefore E = + 3°.

This represents the quadrantal action of unsymmetrical horizontal soft iron which, if it existed alone or without D, would be corrected by spheres placed with their centres in the plane of the needles and on a line at 45° with the fore and aft line, in this case from the port bow to the starboard quarter.

The expression for the total quadrantal deviation being D sin 2 Co. + E cos. 2 Co. might be written as

$$D \left(\sin 2\ \text{Co.} + \frac{E}{D} \cos.\ 2\ \text{Co.} \right)$$

Now, since the tangents of angles may have any value from 0 to infinity, let M be an angle such that $\frac{E}{D} = \tan 2\ M$, then, on substituting the value of E in terms of M, we find the expression for the whole quadrantal error becomes D (sin 2 Co. + tan 2 M cos. 2 Co.) = $\frac{D}{\cos.\ 2\ M}$ (sin 2 Co. cos. 2 M + cos. 2 Co. sin 2 M) = $\frac{D}{\cos.\ 2\ M}$, sin (2 Co. + 2 M), which we see has its greatest value when (2 Co. + 2 M) = 90° or 270°, since then its sine = 1, such maximum value being $\sqrt{D^2 + E^2}$, if we express cos. 2 M in terms of tan 2 M, since for these values of (2 Co. + 2 M) we find cos. $2\ M = \pm \frac{D}{\sqrt{D^2 + E^2}}$

In other words, when both D and E exist, their united effect may be represented by the action of a horizontal soft iron rod pointing to the centre of the compass, and inclined at an angle, M, to the fore and aft line, which will be corrected by spheres placed on a line at right angles to this direction.

Thus, if D and E are equal and both +, tan 2 M = 1, and therefore M = 22½°, so that the united action of D and E could in this case be represented by such a soft-iron rod lying two points on the starboard bow, and corrected by moving the spheres until their centres are on a line 22½° before and abaft the beam, the port sphere moving forwards.

In the case we are dealing with, where D = + 8° and E = + 3°, the total action will be represented by that of a horizontal soft-iron rod pointing to the centre of the compass, and lying forward of it and on its starboard side at an angle of 10° with the fore and aft line (since 2 M now equals 20°, being an angle whose tangent is $\frac{E}{D}$ or $\frac{3°}{8°}$ = ·37), and will be corrected by rotating the spheres until the line joining their centres lies at an angle of 10° with the midship line, the port sphere moving forwards.

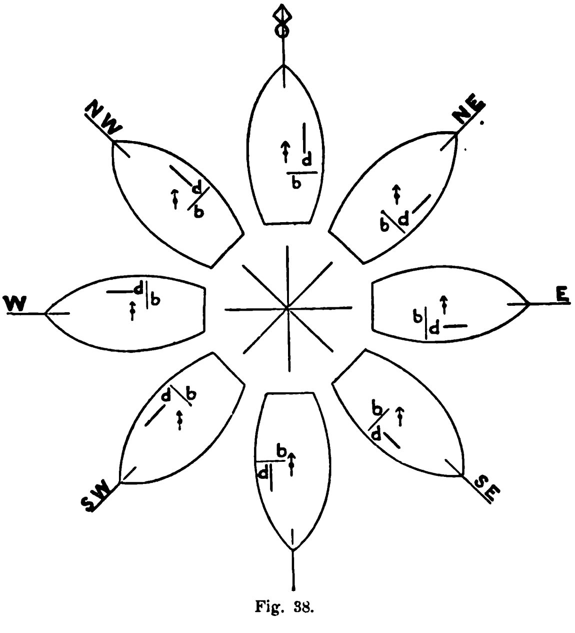


Fig. 38.

From this we see that while the separate parts of the quadrantal deviation have their neutral points on the cardinals and quadrantals, and their maximum points at 45° or four points from these, the neutral points of the *whole* quadrantal deviation will in this case be found at N. 10° E., E. 10° S., S. 10° W., and W. 10° N., the maxima points being nearly at 45° from that.

Co-efficients A and E, both arising from the action of unsymmetrical soft iron, are intimately connected, and the correction of E will affect the value of A, so that the constant part of the deviation when it exists will not have the same value after E is corrected as before. The connection between these two sources of error, in another case, will be seen from Fig. 38, where we suppose that the only forces disturbing the compass emanate from two horizontal soft-iron rods, *d* and *b*, of which the former when acting most powerfully will cause 9° of deviation, and the latter 1°. The united effects of these on the cardinal and quadrantal points will be to give at North + 9°; N.E. + 5°; East + 1°; S.E. + 5°; South + 9°; S.W. + 5°; West + 1°; and N.W. + 5°, or if shown on a curve will be represented by Fig. 39, which we see is evidently found by the union of a quadrantal curve due to E = + 4° and a constant error of A = + 5°.

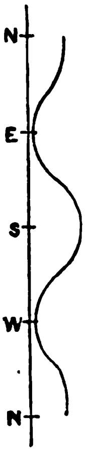


Fig. 39.

It should be observed that horizontal soft-iron might be unsymmetrical with regard to a compass, either from such distribution round a compass in the midship line (which is rare) or more commonly from the compass itself being out of the midship line.

We have thus in the simplest way—that is, by using the deviations observed on the smallest number of points absolutely necessary—found the values of the approximate co-efficients, and thus, as it is termed, "analysed" the deviation of a compass, which in the form of a table would have been noted as follows:—

North + 2°; N.E. + 15½°; East + 11°; S.E. + 6½°; South + 12°; S.W. + 8½°; West - 9°; N.W. - 14½°, and on a curve would have been shown as on Fig. 40.

The Manual, on pages 53 to 61, gives methods of calculating these co-efficients more accurately by employing the deviations found on 32, 16, or 8 points, such methods being derived by similar ordinary algebraical processes on substituting observed deviations in the original equation (2) on *page* 54 simplified by observing on points equally distributed round the compass. It must be remembered, however, that although by employing the deviations observed on a large number of points, increased accuracy in the values of the co-efficients results, yet whether we use few or many points we only obtain the approximate co-efficients as long as they are derived from the approximate fundamental equation.

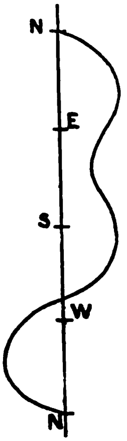


Fig. 40.

The connection between approximate and exact co-efficients, when the deviation does not exceed 40°, is given on page 62 of the Manual. With deviations exceeding 40° this connection is only approximate.

This connection may perhaps be made more clear by Fig. 41, where the ship's head is represented as being East by compass, on which point the whole fore and aft magnetism of the ship, or co-efficient B, must be producing its most powerful effect, and, if acting by itself, would be measured by the sine of the deviation produced; but since the ship's head is not East (*magnetic*), the north part of the needle, and therefore the deviation, is slightly affected by the athwartships magnetic force of the ship, or co-efficient C, and also partly by the horizontal soft iron causing co-efficients D and E; moreover, the forces composing B are not acting at exactly the same angle, with regard to the compass, as they would be if C, D and E did not exist, so that the exact co-efficient B will differ from the sine of the corresponding approximate co-efficient by small actions arising from the other co-efficients, and similarly with the exact A, C, D and E.

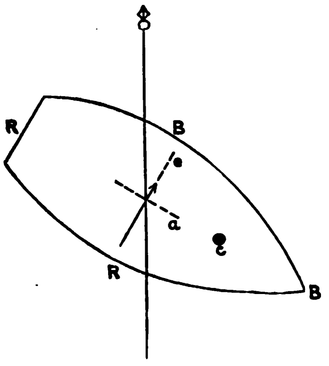


Fig. 41.

Since, for the purpose of correcting the heeling error and determining the mean directive force, we have to employ the exact co-efficients, it is usually more simple to obtain these directly from the exact fundamental equation (1) on *page* 53 than to first find the approximate co-efficients and then transform them into those which are exact.

The method of doing this is not quite so simple as that which we have explained, but the working formulæ obtained, adapted to observations made on either eight, five, four, or three principal points, are given on pages 120 to 124 of the Manual.

those for eight points being usually employed where probably A and E exist, otherwise the more simple quadrant formulæ for three points suffices.

In practice, we start adjusting an uncorrected ship by observing, as we have seen, the deviations on the principal points, and from these, expressed either in a table or curve (or usually in both), we deduce the values of the co-efficients, both exact and approximate. Though not practically required, it will be instructive for us now to reverse the operation and see how the original curve is built up by the combination of curves

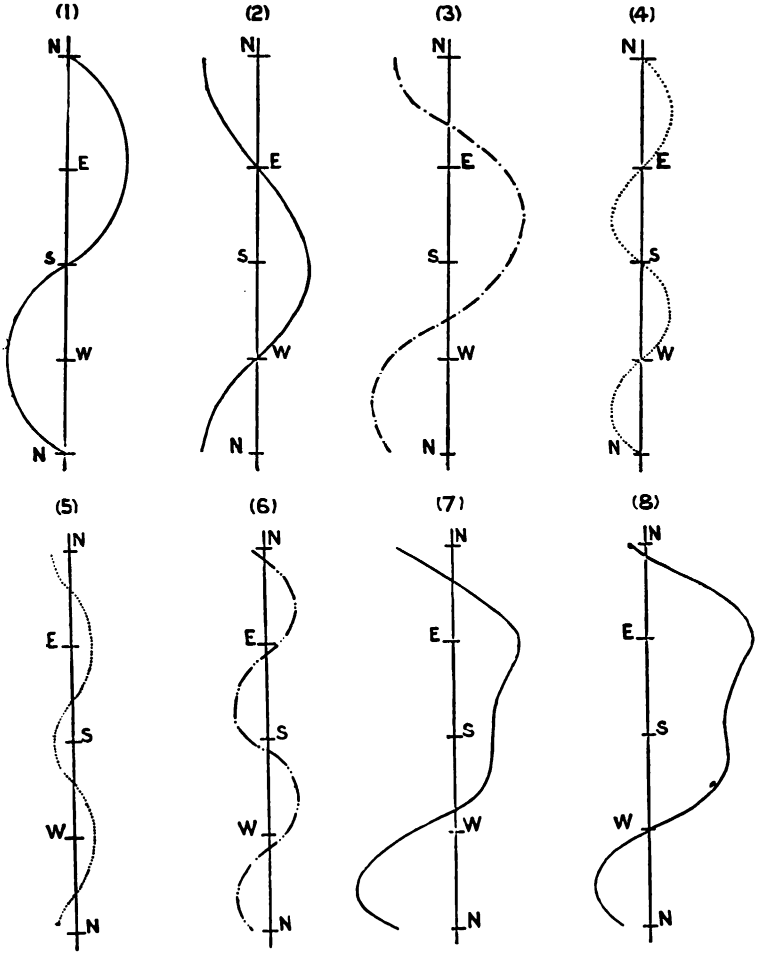


Fig. 42.

which each of the five co-efficients will give rise to. Thus, suppose that at another compass in the same, or another, uncorrected ship we have found the values of the approximate co-efficients to be as follows :—

A = + 3°; B = + 10°; C = - 8°; D = + 5°; E = - 2°.

Beginning with co-efficient B, or the total fore and aft magnetic pull of the ship, this will give us curve (1) of Fig. 42, while C, or the total athwartships pull, gives curve (2).

The united effects of B and C is shown on curve (3), which is that of the whole semi-circular error (B sin Co. + C cos. Co.)

Similarly, curve (4) shows the effect of D, the symmetrical part of the quadrantal, and curve (5), that of E, the unsymmetrical portion of the same; their united effect, on curve (6), showing that caused by the total quadrantal error (D sin 2 Co. + E cos. 2 Co.).

On similarly bringing together in one curve (3) and (6), we get one, (7), representing the combined action of B, C, D and E. If now the central line be shifted parallel to itself, and 3° to the westward, or left, we introduce a constant error of + 3° on every point, and thus allow for co-efficient A, (8), so that if from the original observed deviation we had plotted a curve, as usual, it would, in this case, be of the form finally assumed in (8).

From a careful consideration of the very important subjects dealt with in this Lecture, we see, as before mentioned, that when a ship is upright we can accurately represent the deviation at any compass by the action of bar magnets and soft-iron rods.

If the compass is in the midship fore and aft plane, with iron symmetrically distributed round it, two magnets will represent the permanent magnetism of the ship (P and Q), and a vertical soft-iron rod (*c*) the effect of the ship's vertical soft iron; the united effect of these three representing the semicircular deviation, or co-efficients B and C. The quadrantal error, or co-efficient D, can be represented by two unequal soft-iron rods—one, (*a*), fore and aft, and the other, (*e*), athwartships.

At a binnacle compass, or one out of the midship line, the additional errors would require for their representation three more soft-iron rods—one fore and aft, (*d*); one athwartships, (*b*); and one vertical, (*f*).

When we reach our Lecture on the heeling error, we shall see that the additional error introduced by the heeling of the ship can be represented by the actions of a vertical bar magnet, to correspond to the vertical permanent force of the ship, (R); one fore and aft soft-iron rod, (*g*); and one vertical soft-iron rod, (*k*); so that at any compass in any ship, whether upright or heeled over, we can accurately represent the deviation by the united actions of three bar magnets, and some, or all, of eight soft-iron rods.

For illustrative purposes, this is admirably embodied in the well-known model much used for teaching purposes, and known as Beall's deviascope.

EXAMPLES.

1.—Analyse the following deviation tables, finding in each case the approximate co-efficients, and drawing, approximately, the original curve and those caused by each co-efficient separately.

(a)

North	4° W.	South	3° E.
N.E.	25° E.	S.W.	14° W.
East	29° E.	West	29° W.
S.E.	19° E.	N.W.	28° W.

(b)

North	5° 0′ E.	South	5° 0′ E.
N.E.	2° 40′ E.	S.W.	2° 50′ W.
East	1° 0′ W.	West	9° 0′ W.
S.E.	2° 40′ E.	N.W.	2° 30′ W.

2.—Two compasses between decks were compared with the Standard when a ship was swung. Calculation gave the following co-efficients :—

Fore Compass.	After Compass.
A = − 7°, D = + 20°, E = + 8°.	A = − 6°, D = + 2°, E = − 6°.

Describe how the compasses may be corrected.

LECTURE VI.

Directive Force acting on a Compass—Effects of Hard and Soft Iron—Measurement of λ—The Deflector.

Experience shows that in an iron ship after accurate correction for every kind of deviation, all compasses, though differing from each other, exhibit on every point a diminution of directive force or pointing power as compared with that on shore; in the case of the same ship when uncorrected, additional causes are acting, which often become strongly marked when the ship's head is in certain directions, and cause either increased or decreased directive force as compared with that on shore; such causes, however, on the whole, will nearly balance each other, or in other words, the mean of the directive forces on equally distributed points in an uncorrected ship will generally practically equal that on any and every point in the same ship after correction, both being less than that found on shore or in a wooden ship, and having very different values at different compasses on board. A decrease of directive force produces these effects:—(1) it makes a compass, sluggish, or slow to respond to quick alterations of course, (2) if any disturbance sets it swinging, it is long in coming to rest, and (3) it augments the effects of many causes producing deviation: thus a magnet, which on shore or in a wooden ship disturbs a compass 5°, would under similar circumstances of distance and position disturb it 10° in an iron ship, supposing that the pointing power of the compass was there diminished by one half.

In seeking for causes of this loss of mean pointing power, let us first consider the case of a ship built entirely of hard iron, with her head at that time N.E. magnetic. From Fig. 43 we see that with her head in this direction there will be a loss of directive force in either hemisphere, and with head S.W. magnetic, an equal increase of such power, no deviation, however, being experienced on those points.

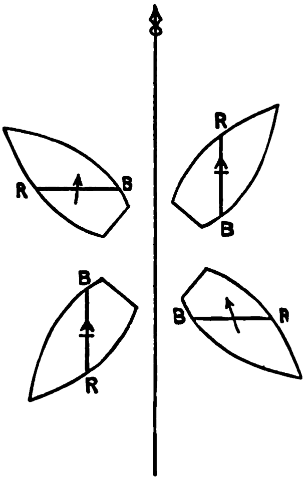


Fig. 43.

At S.E. and N.W. magnetic, great deviations will be produced, but the directive force will not be affected, so that from this cause (hard iron), though the pointing power will greatly vary on different points, its mean value, or that on equidistant magnetic points, will be unaffected by the ship and remain the same as on shore or in a wooden ship.

Vertical soft iron, before or abaft the compass, in a similar way, will be found to affect directive force at North and South magnetic, but not at East and West magnetic.

If before the compass it will, in the northern hemisphere, increase the pointing power at North and equally decrease it at South (Fig. 44), while in the southern hemisphere it will decrease it at North and increase it at South, opposite effects in each case occurring if such iron is abaft the compass. In all cases, however, the *mean* result will be unaffected.

Here it will be noticed that the hard and vertical soft iron of a ship, which acting in combination, cause the whole of the semicircular deviation, separately affect the directive force most on those points where they individually produce no deviation, and not at all on those points where they (approximately) individually produce their greatest deviation.

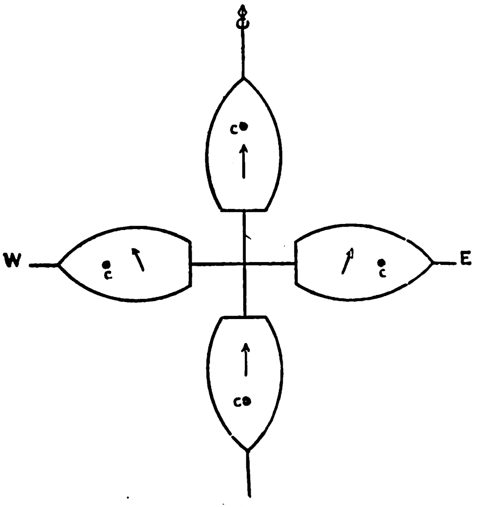


Fig. 44.

The action of symmetrical, horizontal soft iron, represented by fore and aft and athwartships iron rods (*a* and *e*), is different to the foregoing, since these are magnetised temporarily by the action of the earth, so that, irrespective of the direction of the ship's head, their ends nearest the north in all latitudes have always red magnetism, and those nearest the south blue magnetism.

From Fig. 45 it will be seen that rod − *a* will decrease directive force equally at North and South magnetic, and rod

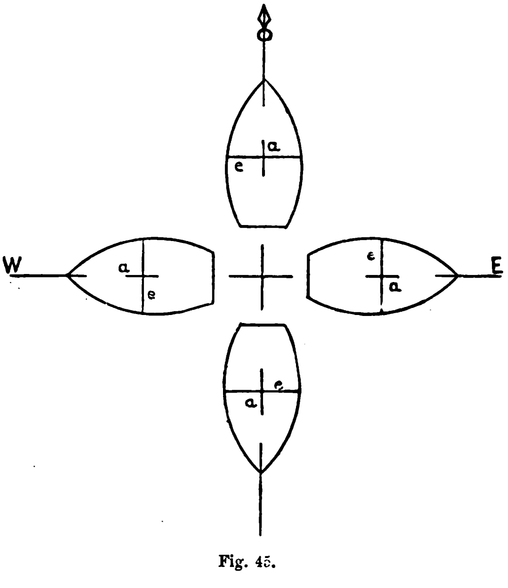


Fig. 45.

+ *a* will similarly, equally increase it on those points, neither + *a* or − *a* producing any effect at East and West magnetic (since they are not then magnetised); rod − *e* will similarly diminish directive force by equal amounts at East and West magnetic, and produce no effect at North and South; if rod − *e* equals rod − *a*, an equal decrease of directive force will be found from their united action on all points, but no deviation—which is exactly what generally occurs when a ship is completely adjusted—but if, as usually happens before correction for quadrantal error, rod *e* is more powerful than rod *a* the directive force will be unequally diminished, the greatest diminution occurring at East and West magnetic, which is exactly what occurs when a ship is corrected for semicircular deviation only, and is the reason why the correction of co-efficient D, by equalizing rods *a* and *e*, slightly increases the mean directive force.

From the foregoing we see that the application of correctors, in the forms of magnets and Flinders' bar, cannot affect the *mean* directive force acting on a compass, as they produce contrary effects on opposite points, but a reference to Fig. 36 shows that the soft iron spheres used for quadrantal correction weaken directive force with the ship's head at North and South, and increase it when heading East and West, such maxima and minima points being at right angles and not opposite to each other.

Similar considerations to the foregoing will also show that unsymmetrical, horizontal soft iron (causing A and E), will slightly affect the pointing power on individual points, but will scarcely affect the mean value, and as these co-efficients are usually very small we shall disregard them from our present point of view.

This mean or average directive force at a compass which we have been referring to is technically known as λ (lambda), and may be regarded as either (1) the directive force on any point in an accurately corrected ship, or (2) practically, but not quite exactly the mean of such forces at four or more equidistant magnetic points in the same ship before correction, or (3) the force at any one point in the uncorrected ship when freed from the action of the causes producing semicircular and quadrantal deviations on that point; this last method being the usual way of determining it.

λ is always expressed in terms of the horizontal magnetic force on shore at the place of observation taken as unity, and for the same reason that the quadrantal deviation remains everywhere the same *(page 44)*, so the mean directive force at the same compass will everywhere bear the same ratio to the earth's horizontal force at the same place.

Thus, when we say that ·8 is an ordinary value for λ at a standard compass in a battleship, we mean that everywhere such a compass, completely corrected for deviation, will be pointing on every point with only $\frac{8}{10}$ of the power with which it would do so on shore or in a wooden ship at the same place.

Each compass in a ship has its own particular value of λ, and if necessarily placed so as to be surrounded by much soft iron (as inside a conning tower), its value is sometimes as low as ·1, which may be accounted for when we think that, irrespective of the direction of the ship's head, the part of the conning tower towards north will always have red magnetism and thus oppose the north end of the needle, weakening everywhere its pointing power.

From this we also see, that in originally selecting a position for a standard compass the chief point to be considered is not so much the all round view from it, or the smallness of the deviations observed, as to place it where the strongest directive force can be obtained.

Since the quadrantal deviation and λ alike depend upon the action of horizontal soft iron when *both* are determined at a compass, the relative proportions of the fore and aft and athwartships components of this soft iron can be found *(see page* 107 *of* Manual; in this way the values and positions of rods *a* and *e* for different ships, given in Table 6 of the Manual, are arrived at.

To illustrate the connection between λ and D, suppose we take the fore bridge compass of the "*Powerful*," where, as given in that Table, we see that the fore and aft symmetrical soft iron in the ship *(a)*, by the induction of the earth's horizontal force is magnetised with ·032 of its own power, such an amount depending, in each individual case, on the nature and quality of the iron; we also see that, by the same agency, the athwartships soft iron *(e)* is endowed with ·388 of the earth's horizontal force.

As the distribution of the iron considered is symmetrical and minus (which is equivalent to considering each rod to pass through the compass), if we consider the earth's horizontal force to be 1, we see (Fig. 46) that at both North and South magnetic (*e* not now acting) the pointing power will be ·968 or (1 − ·032).

For similar reasons at both East and West magnetic (*a* not now acting) the pointing power will be ·612 or (1 − ·388), so that the mean directive force will be ·790, corresponding to what is given as the value of λ.

A similar result would be found if we had taken the mean of the directive force acting towards north on any four or more equidistant magnetic points: the value of λ given in this Table is that found *before* the quadrantal deviation is corrected, in the present case that correction would mean altering the value of *e* from − ·388 to − ·032, thus making it equal to *a* and increasing λ from ·790 to ·965.

An examination of Fig. 46 will show that the soft iron rods causing quadrantal error affect the pointing power most and

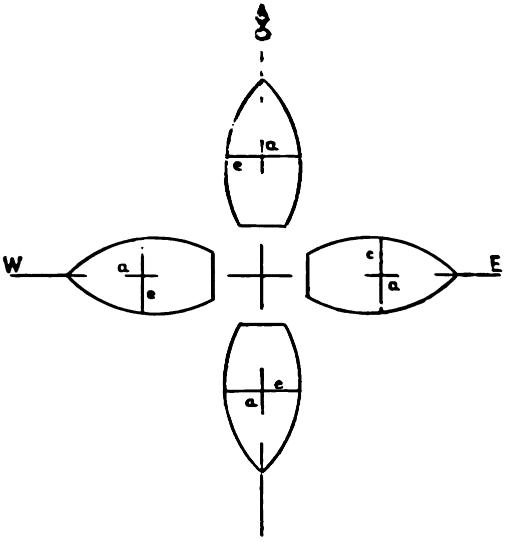


Fig. 46.

least at points 45° from where they cause most deviation, and as when the ship is turned completely round each rod will twice cause its greatest effect and twice none at all, the *mean* effect will be a half of each maximum; such mean effect will cause the pointing power on board, or λ, to equal the horizontal force or pointing power on shore, plus half the effect of *(a)* and plus half the effect of *(e)* or, if we call the horizontal force on shore 1, then $\lambda = 1 + \frac{a}{2} + \frac{e}{2}$ which, on giving proper signs to *(a)* and *(e)*, agrees with the preceding.

Before correction, when the ship's head is N.E., rod *a* will be acting with a power of ·032 × cos. 45° = ·0224 of the earth's horizontal force, and as this acts in a N.E. direction it will weaken the *earth's* directive force (or 1) by ·015, being ·022 × cos. 45°, and cause an equal pull of ·015 to the westward.

Similarly, rod *e* will on this point weaken directive force by ·19 and cause an equal push to the eastward, the united effect being to cause a deviation of 11° E. $\left(\text{whose tangent is } \frac{\cdot 19 \quad \cdot 015}{\cdot 965}\right)$ being that given in the table as the value of D.

It is instructive to similarly examine the values of D and λ for other compasses given in this table.

A large quadrantal deviation (D) is, as we see from Table 6, usually associated with a considerable *difference* between the values of *a* and *e* (both being negative), irrespective of their individual values.

If such values are both large, λ is small, but if, while their difference is great their individual values are small, λ will be great.

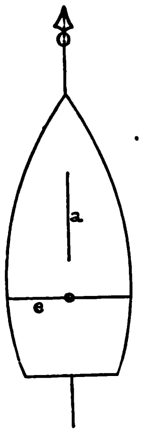


Fig. 47.

A somewhat exceptional case is where *a* is great and + while *e* remains great and — ; in this case (Fig. 47), both D and λ have large values.

To determine the value of λ, we want to compare the horizontal magnetic force acting on the compass with the similar force acting on shore. For this purpose the best results are obtained by comparing the rates of oscillation of a small horizontal magnetic needle on shore with that found when it is mounted in exactly the same position on board as the compass needles.

A horizontally suspended magnetic needle on shore, drawn out of its position of rest, will swing to and fro under the influence of the earth's horizontal magnetism, in a similar way to that in which a free vertical pendulum, similarly treated, swings to and fro under the influence of gravitation, the laws governing its movements being practically the same; the period of swing will chiefly depend upon its length, weight, shape, magnetic power, and the horizontal force of the earth at the place, and will be practically the same whether drawn out of its position of rest through a small or large angle (up to 30° on either side).

If the means of the times of several sets of, say ten vibrations are taken at two different places on the earth, the horizontal magnetic forces of the earth at each can be directly compared with each other, the needle vibrating most rapidly where the earth's force is the greater and *vice versâ* ; thus, if at A the needle makes ten vibrations in 21 seconds, and at B it makes ten vibrations in 15 seconds, then the force at B : force at A : : $21^2 : 15^2$, or it is nearly twice as great.

The same result would be obtained by, in each case, noting the number of vibrations occurring in the *same* time ; thus, if at one place, C, the needle makes 10 vibrations in a certain time, and at another, D, the same needle makes 12 vibrations in the *same* time, then the horizontal magnetic force at C is to that at D as 10^2 is to 12^2, or 5 to 7 nearly.

From the results of such observations as these, made at different places, Chart No. 3 of the Manual (also given as No. 1

at the end of this book), showing curves of equal horizontal force, was drawn.

The pointing power on board ship is compared with that on shore in precisely the same way, but in all cases we must remember that we are comparing the forces with which the compass is pointing in the direction of its own length or that in which it lies; on shore this is, of course, directed to North magnetic, but on board an uncorrected ship may widely differ from this, so that our ship observation must be multiplied by the cosine of the deviation from magnetic North, so as to make the two observations on shore and on board similar.

Thus suppose the time of making ten vibrations on shore to be 21 seconds, and that on board 19 seconds, the compass having 20° of deviation on the point on which she was lying when the observation on board was made.

Then $\frac{21^2}{19^2} = \frac{441}{361} = 1{\cdot}221$ represents (in terms of the shore force considered to be 1) the force with which the needle points on board in the direction of its length, so that $1{\cdot}221 \times \cos. 20°$ $= 1{\cdot}147$ represents the force with which, on that particular course, it points to magnetic North.

(1) If the foregoing experiment were carried out at a compass in a perfectly corrected iron ship, we should find the same result on every course, the pointing power being everywhere equally diminished as compared with that on shore.

(2) If in the same ship, before correction, we had made such observations with the ship's head on any four equidistant magnetic points (Fig. 48), we should find that, although the individual results would probably greatly vary, the mean would generally be practically the same as in case (1), unless the quadrantal deviation (D) was very great, or, in other words, rod *(e)* was much more powerful than rod *(a)*, both being –, when the result would be less than in case (1).

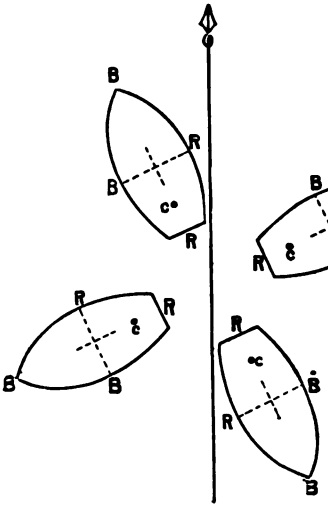


Fig. 48.

(3) If, in the same ship, before correction, the observation for λ had been made on only

one point (as is usually most convenient to do), we should find that, although in that particular direction of the ship's head the directive force might be either much greater or less than on shore, yet, if we could eliminate the actions of hard iron, vertical soft iron and horizontal soft iron (represented by *exact* co-efficients B, C and D), we should get the same results as in case (1); in practice, therefore, the ship is first swung and the co-efficients calculated, this showing one important object in obtaining them.

The working formula in this case is

$$\lambda = \frac{T^2}{T_1^2} \times \frac{\text{Cos. dev. (on point of observation)}}{1 + B \text{ cos. Co.} - C \text{ sin Co.} + D \text{ cos. 2 Co.}}$$

when T and T_1 are the times of making a similar number of vibrations of the horizontal needle—say ten—on shore and on board respectively. B, C and D are exact co-efficients, and Co. is the magnetic direction of the ship's head at the time of observation.

Observations for λ are necessarily made with the ship at anchor in still water.

Similar results to those obtained by vibrating a horizontal needle can be arrived at in another and more simple way by applying the principle, that if by some means (usually a magnet) we draw the north point of a compass 90° out of the meridian, either way (termed a normal deflection), the power employed to do this, if acting at right angles to the north and south line of the compass, must be equal to the force which causes the compass to point to the north. Such disturbing power is applied by deflecting the compass by means of a magnet placed over it, and kept broadside on to the needle.

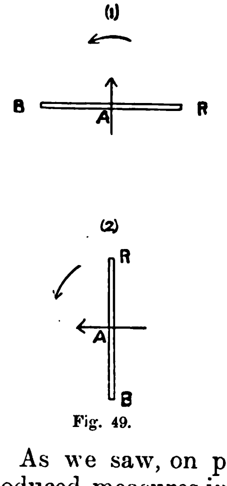


Fig. 49.

Thus, in Fig. 49, the north point of the compass, A, will be deflected to the westward by a magnet, B R, whose middle point is placed vertically over or under its centre, and can be made to assume the position (2) by regulating the length of the disturbing magnet, which must be kept with its middle point at a fixed distance from the centre of the compass and always with its axis over its east and west line.

By making observations exactly similar to this both on shore and on board, we can compare the horizontal force acting on the compass in each case.

As we saw, on pages 7, 18, the natural sine of the deflection produced, measures in terms of the pointing power the disturbing force acting (if applied in this way), so that as sine 90° = 1 when the deflection is 90°, the power acting to disturb the compass equals that with which it is pointing.

From this comparison, if we consider the force on shore as 1, we can, as before, in either cases (1), (2), or (3), find the value of λ.

The regulation of the length of the disturbing magnet referred to is practically obtained by using one formed as in Fig. 50, by hinging two similar bar magnets at dissimilar poles, and mounting them over a scale of equal parts, so that their free poles can be separated by a distance read off in scale divisions.

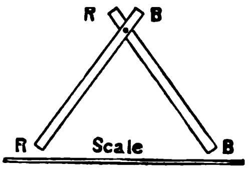


Fig. 50.

Such adjustable poles, though having no material connection, are equivalent to a horizontal bar magnet of variable length, and represents the principle of the well-known "Deflector" of Lord Kelvin.

Thus, suppose that on shore the normal deflection of 90° is obtained when the deflector, applied as above, reads 15·2 divisions, and at a compass on board ship the normal deflection is similarly obtained, with a reading of 7 divisions.

If experiment shows that on shore a reading of 7 divisions only deflects the compass 53½°, we find that the pointing power on board (in the particular direction of the ship's head) : horizontal force on shore : : sine 53½° : sine 90°, or if we consider the earth's horizontal force as 1, that on board is ·8.

From this, as before, we can find the value of λ.

The disturbing magnet, or deflector, may be either applied as described, by keeping its axis over the East and West line of the compass (broadside on), when its action, as compared with the horizontal force of the earth, will be measured by the natural sine of the angle of deflection produced, or it may be placed with its axis kept on the *magnetic* East and West line, when the tangent of the angle of deflection gives the same result.

The co-efficients themselves, in an uncorrected ship, could be found by the deflector in a precisely similar way by comparing the scale divisions required to obtain the normal deflection on board on each of the eight principal compass points with that required to do so on shore, thus offering an alternative mode of procedure to that of using deviations found from bearings.

From the foregoing, we see the connection between the directive force acting on a compass and its deviation; also, that when the former is made equal on all points (though everywhere less than it is on shore), there can be no deviation.

Equalization of directive force on five selected points, in an uncorrected ship, will effect this result, while making it equal on four selected points will do so, if, as in all sea-going ships, the quadrantal error be corrected.

This leads us to the explanation of the method of adjusting a compass without using bearings, generally known as the "Deflector Method," and which is extensively used, both for original correction and for that necessitated after such correction by changes which may occur during a voyage, and especially when cloudy weather prevents other methods of doing so from being practised; theoretically, such a mode of compensation could be applied to all compasses, but, practically, the results would not be sufficiently accurate, unless the card were light and the needles short and weakly magnetised.

Taking first one, probably, of the most useful applications of this method, suppose that in a sea-going ship (having quadrantal error corrected), owing to cloudy weather, no opportunity has occurred of obtaining the deviation for some days, during which, from sub-permanent magnetism, change of dip, or other causes, there is reason to believe that the deviation has most likely changed by an unknown, though comparatively small, amount (say 5° or 6°), which yet is probably too great to justify making the land without knowing its value or correcting it. On the reasonable supposition that such error is of a semicircular character, we might proceed as follows:—

As the ship's head cannot, in the case we are considering, be placed on magnetic points, we steer North by the compass we wish to correct, and the circumstances of weather and sea must be such that by means of another compass we can keep her head within a degree or two on either side of this direction for about ten minutes.

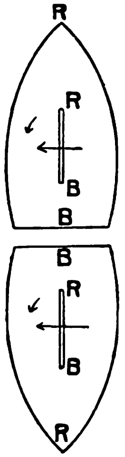


Fig. 51.

If we place over the East and West line of the compass, and at a certain distance from its centre, a magnet having, say red to starboard, the north end of the needle immediately moves to port, and by following it up we find, with—say a magnet 5 inches long—we at last deflect the compass through an angle of 90°, so that the East point is under the lubber line, the disturbing magnet standing as in Fig. 51, and its power now equals the directive force with which the needle is trying to point to North. The magnet is then removed and the ship turned sixteen points, so as to be now heading South by compass, when, on exactly repeating the above experiment, we will suppose that a 6-inch magnet is now required to obtain the deflection of 90°.

Since more power (indicated by a greater length of magnet) is required with head South than with head North to obtain the same deflection, it shows that in the former case the compass is pointing more strongly, which indicates that the ship has acquired blue magnetism in the after part, and if no fore and aft magnets are in position, some must be introduced, with red poles aft, and raised until, with a disturbing magnet 5½ inches long (being the *mean* of the lengths required at North and South), we get a deflection of 90°; when this takes place, we shall have evidently equalised the pointing powers at North and South (since, in either case, a 5½-inch magnet will now give the normal deflection), and therefore corrected the deviations at East and West.

Usually, corrector magnets will already be in the fore and aft holes in the binnacle, so that if their red poles are aft they will require raising, and if blue aft, lowering until the desired deflection of 90° is obtained with the 5½-inch magnet.

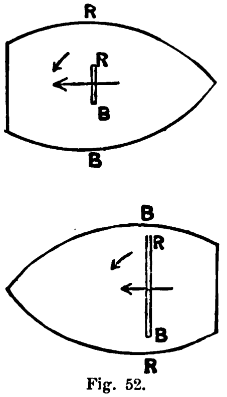


Fig. 52.

Exactly similar observations are now made with the ship's head East and West by compass (Fig. 52), and if in the first case, to obtain the deflection of 90° requires the application of a 4-inch magnet, and in the second, that of a 7-inch magnet, this shows that the compass is pointing more strongly at West than at East, and that the ship has acquired blue magnetism on the starbord side.

Taking now a magnet 5½ inches long (the mean of the lengths required at East and West), we make the deflection 90° by introducing corrector magnets in the athwartships holes, red poles to starboard, or if, as would usually be the case, magnets are already there, they must be raised or lowered in a corresponding way.

The pointing power at East and West being now equalised, the deviations at North and South will be corrected, and in the case we are considering, since the means of directive force at East and West now equal the means at North and South, the compass should be correct on all points.

In practice, if we began with head North, we should turn to either East or West, and then, continuing to turn in the same direction, correct with magnets on the two other cardinal points; the lengths of the magnets given in the above example would, in using the deflector, be represented by the number of scale divisions by which the poles are separated.

Theoretically, it is indifferent whether the compass be deflected to the right or to the left, but in practice, since we are making comparisons of one measure with another, they all four should be made in exactly the same way and, although the deflector is most powerful when the pointer is over the East point of the compass (its line of poles then lying at right angles to the North and South line of the compass),yet in practice it is more convenient to place it *near* east (usually over E. by N.), so that a slight movement towards east will increase its influence over the compass, and towards north will decrease its power; the essential point is that while the pointer might be over *any* point (if the same in all four cases), the deflection must always be within a degree or two of 90° (normal deflection).

If adjusting a compass which has not been corrected for quadrantal error, the mean of the deflector readings at East and West will always be less than the mean of those at North and South; this is explained (Fig. 45) by the excess of the power of rod *e* over that of rod *a*, which, as we have seen in Lecture 4, is exactly what causes quadrantal deviation (D); thus we see from the figure that the pointing power, with the ship's head both East and West, will be decreased more than it is both at North and South, and therefore, the deflection obtained with a smaller scale reading on the deflector.

To correct this quadrantal error when the ship's head is on any cardinal point, either before or after the semicircular correction, the spheres should be mounted on their brackets and approached until the deflection of 90° is obtained, with the deflector set to the mean of all four readings found at North, South, East and West.

If now, when the ship is turned to a quadrantal point, the deflector set to the last or mean reading does not deflect the compass 90°, it shows the existence of co-efficient E, or that part of quadrantal error arising from unsymmetrical soft iron, and the line of the centres of the spheres must be rotated and the spheres themselves approached until the desired effect is obtained with this scale reading.

This, as previously said *(see page 48)*, would be difficult to do.

Theoretically, the observations with the deflector should be made on points exactly opposite to one another, or 180° apart, but it will be sufficiently accurate in practice to put the ship on opposite *compass* points if the deviation be not greater than 10°, which will be known to be the case if the deflector readings on opposite cardinal points differ from each other by less than ten scale divisions; if more than this difference is observed, the ship must be again turned round and re-adjusted as before.

In adjusting a new ship having very large deviation (40° or 50°), it is more expeditious to begin by roughly placing the ship's head on magnetic points by bearings, and reducing somewhat such excessive errors.

EXAMPLES.

1. An iron ship was built with head S.E., and had a vertical soft iron rod *(c)* before the compass, and a horizontal athwartships soft iron rod *(e)* under the compass.

How would the directive force in both magnetic hemispheres be affected when ship's head was at N., S., E., and W. respectively—(1) by hard iron of ship; (2) by the vertical soft iron; (3) by the horizontal soft iron?

2. A standard compass deviated 3°, caused by the disturbing force of the ship's permanent magnetism, and when the directive force acting on the compass = ·85; how much would the same compass deviate in a conning tower where the directive force is ·25, supposing the same disturbing force to act upon it?

Answer:—10°.

3. A compass was placed in a binnacle on shore where the earth's horizontal force = 1·0. A horizontal magnet fixed 20 inches below the compass caused 3° of deflection in the card. A pair of soft iron spheres secured on the brackets caused 6° of deflection. Without moving magnet or spheres, the compass and binnacle were carried on board a ship where the mean horizontal force was only 0·3. How much deflection of the card would the magnets now cause and how much the spheres?

Answer:—10°; 6°.

4. The normal deflection of 90° was obtained with a deflector as a ship's head was placed on the four cardinal points with the following scale readings:—

North = 24. East = 21.
South = 18. West = 21.

Describe how the compass should be corrected.

5. A ship in a fog was steered on the four cardinal points of the compass, and the normal deflection by deflector was obtained with the following scale readings:—

North	40°	East	32°
South	10	West	20
	—		—
Mean =	25	Mean =	26

The compass was then corrected by magnets, using the above mean values. Do you consider the compass will now be practically correct and suitable for shaping a course by, or must a second round of observations be made?

6. A ship in a fog was steered on the four cardinal points of the compass, and the normal deflection was obtained with the following scale readings:—

North, 40 divisions.	East, 32 divisions.
South, 10 „	West, 20 „

State how you would correct the compass.

7. In a ship swung by deflector, the normal deflection of 90° was obtained with the following scale readings:—

Head, N. 18; S. 24; E. 20; W. 18.

What correctors should be used, and how should they be placed?

LECTURE VII.

Heeling Error—Causes and Effects of—Correction by Vibrations—Correction by Balanced Horizontal Needle.

Hitherto we have only considered the disturbing effects of the magnetic forces due to various kinds of iron in a vessel, as affecting a compass when the ship is upright, the vertical components of all such forces, obviously then, not producing any deviation, but only tendencies to pull the north end of the compass down, or to thrust it up. When heeling, however, such components all produce very marked horizontal effects, but before examining these in detail, it will be well from a general point of view, to realize the action under such circumstances of a single force—usually the united effect of several—which, when the ship is upright, acts either upwards or downwards.

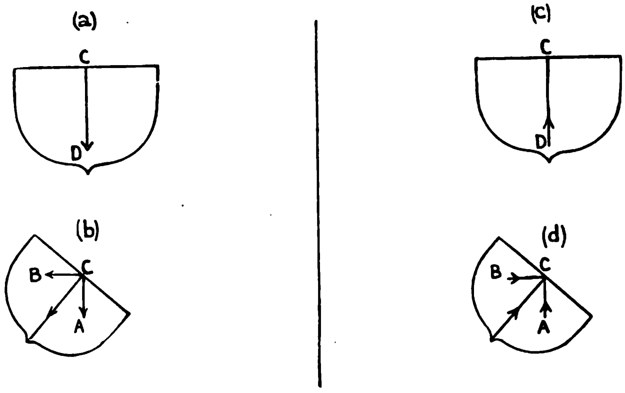


Fig. 53.

Suppose, as in Fig. (53 *a*), that a compass C is acted on by a force C D in a downward direction, or towards the keel, when the ship is upright; on heeling to starboard or to port (Fig. 53 *b*), this one force, C D, acting at the centre of the compass, becomes equivalent to two component forces, *viz.*, C A, which, acting vertically, produces no deviation, and C B, which, acting horizontally, will draw the north end of the needle to the high side of the ship; C B will evidently become greater as the heel increases, until when the ship is on her beam ends, the force C D, which in Fig. (53 *a*) is entirely vertical, becomes entirely horizontal.

As in this case, heeling either to starboard or to port, draws the north end of the needle to what becomes the high side of the ship, this error is technically termed positive (+) heeling error.

If similar figures be drawn on the supposition that the compass is placed over a force, which, when the ship is upright, acts upwards or from the keel, Fig. (53 *c & d*), it will be seen that on heeling either way the action of this force is to thrust the north end of the needle to the low side of the ship, thus causing what is technically termed negative (−) heeling error.

The + and − signs attributed to heeling error must not of course be understood as representing easterly or westerly errors, they merely indicate opposite results.

The effects of such upward or downward forces being to introduce disturbances which act athwartships, they will produce their greatest consequences, whether positive or negative, when the ship is heading North or South by compass, since they then act at right angles to the needle, and will produce no effect when steering East or West by compass, as they then act in the direction of the length of the needle; as within practical limits of heeling (say 30° on either side of the upright position), the heeling error may be considered to vary as the angle of heel, it is convenient to estimate such error in terms of the change of deviation per degree of heel, that at North and South (by compass) being known as the "heeling co-efficient," and the similar, but smaller, change on any other course as the "heeling error."

The heeling error is of the same sign as the heeling co-efficient, and equals that co-efficient multiplied by the cosine of the compass course. Thus, if a compass has a heeling co-efficient of + 2°, we understand that when the ship is heading North or South by this compass, each degree of heel either way will alter the deviation she has when upright by 2°, the north end of the compass being drawn by that amount to whichever is the high side of the ship. Also, if the same ship is steering N.E. by this compass, the deviation when heeling either way will differ from that when upright by 2° × cos. 45° (1·4°) for each degree of heel, the north end of the needle being again drawn to whichever is the high side; the heeling error will obviously disappear when the course is 90°, as cosine 90° = 0.

From consideration of the foregoing general remarks, it is evident that the effect of heeling error, if not allowed for, will be to produce considerable error in the supposed course of a ship, if remaining, possibly for some days, at a more or less constant angle of heel, such error being greatest when steering a North or South compass course, and disappearing when heading East or West by compass; although modern ships are rarely so circumstanced, the necessity for understanding the causes and correcting the effects of the large heeling errors often now found is much greater than formerly, as the rapidly alternating pulls on the north end of the compass, first to starboard and then to port, as a ship rolls either way, would on most courses soon cause the needle to oscillate violently and render steering impossible, such effect being materially increased by the now general use of compasses of slow period of swing.

The effects of unallowed-for heeling error, if at a constant angle of heel, may be summarised as follows:—

(1). In either hemisphere, on northerly courses, positive heeling error if not allowed for will take a vessel to windward of her supposed course, and to leeward of her imagined course, if steering southwards.

(2). In either hemisphere, negative heeling error will produce opposite effects to these.

(3). However great the heeling error may be, and irrespective of its being + or −, no effect is anywhere produced when steering East or West by compass.

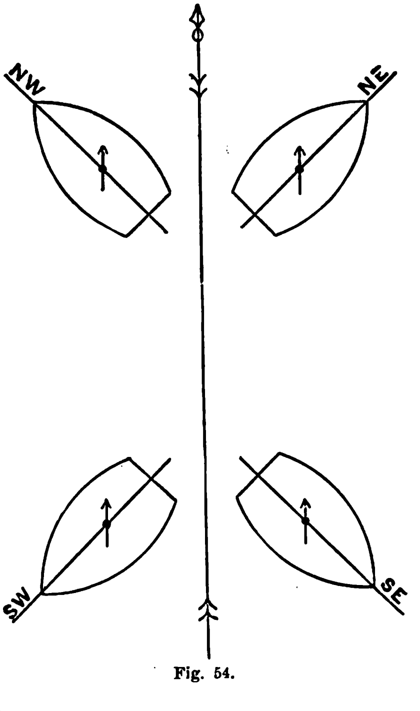


Fig. 54.

Example:—If, in Fig. 54, a compass has positive heeling error, but is otherwise perfectly corrected, and the ship is, when upright, steering N.E. or N.W. by it, since, on heeling, the north point of the needle is drawn to the high side of the ship, when, owing suppose to a northerly wind, she is heeled over and continues to steer N.E. or N.W. by compass, she will evidently go nearer towards the direction of the wind, or to windward, than before, but if the same ship is, when upright, steering S.E. or S.W. by compass, and continues to do so when heeling, under the influence of a southerly wind, she will go farther from the direction of the wind, or to leeward, the effects being the same in either hemisphere.

Negative heeling error would in each case produce opposite effects.

We will now consider in detail the magnetic forces in a ship whose combined action gives the upwards or downwards force we have been dealing with.

The chief among these forces are as follows:—

(1). The vertical part of the same permanent magnetism whose horizontal portion causes part of the semi-circular deviation when upright (hard iron, or R).

(2). The vertical portion of the force induced in soft iron by the action of the earth, whose horizontal part causes the second part of the semi-circular deviation when upright (vertical soft iron, or *k*)

(3). Induction on heeling by the earth's vertical force in the same horizontal soft iron, (*e*), which when upright causes part of the quadrantal deviation (D).

It must not, however, be inferred from this classification that cause (1) is always the greatest, for the relative amounts of causes (1) and (2) most likely differ greatly in ships of different types, and also at different compasses in the same ship; this, however, is a point which has never been thoroughly examined.

In Lecture II. we saw that permanent magnetism (chiefly caused by hammering the skin of the ship while building) turns her into a permanent magnet, the blue and red elements of which are separated by a plane at right angles to the line of dip, so that from this cause we see (Figs. 8 & 10) that the north point of a compass (1) on the after part of the upper deck, in the present case, will, when the ship is upright, experience a downward pull, (+ R), and one forward on the same deck, (2), an upwards thrust (- R).

When this ship heels, compass (1) will therefore from this cause have positive heeling error, and compass (2) negative.

The cause of this part of the heeling error being permanent, and therefore unaffected by change of position, similar effects will be produced on the same course anywhere in the world—

that is to say, compass (1) will everywhere have +, and compass (2) - heeling error, but the *amount* of error at the same angle of heel will vary, as obviously—if we go to a place where, as at Bombay, the compass points twice as strongly as in the Channel, the same disturbing force will only produce half the heeling error, while at a place where the earth's horizontal force is lessened, the heeling error from this cause will be increased.

The second cause of heeling error arises from the action of vertical soft iron, of which, in Lecture III, we only considered the horizontal part of the effect. The other, or vertical component, in Fig. 55, (represented by a vertical soft iron rod (*k*), under the compass if it is on the upper deck), will in the northern hemisphere cause a downward pull on the north end of the needle to compasses placed anywhere on the upper deck—but not necessarily so to those situated below—and, therefore, give to each of them positive heeling error, which will attain its greatest value at compass (2), where the effect of pole B is entirely vertical.

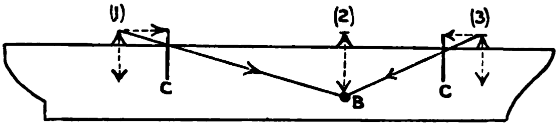


Fig. 55.

This second cause of heeling error does not act at the magnetic equator, where there is no vertical force of the earth, and produces an opposite effect in southern magnetic latitudes; so that on change of positon this part of the error varies, as the tangent of the dip, for similar reasons to those given on page 32.

The third cause of heeling error is induction by the earth in athwartships soft iron, such as *e* (Fig. 56), which, when a ship is upright, is magnetised by the earth's horizontal force only, causing, as explained in Lecture IV., what is, at most compasses, the chief part of the quadrantal error, (D).

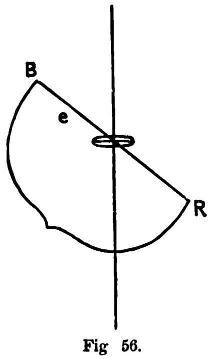


Fig 56.

When the ship heels, such iron becomes magnetised by *both* the earth's horizontal and vertical forces, the action of the former decreasing, and that of the latter increasing, with the angle of heel—the total effect remaining unaltered—until, when the ship is on her beam ends, *e* is magnetised by the vertical force of the earth only, so that, as induction from this vertical force causes the upper part to become blue in the northern hemisphere, it will attract the north end of the needle to the high side of the ship whichever way she rolls, and thus cause positive heeling error. This effect will cease at the magnetic equator and be reversed in the southern magnetic hemisphere, the error varying, as the tangent of the dip, for similar reasons to those given before (*see page* 32).

The whole correction of the heeling error should, theoretically, involve the application of separate correctors for each of these three principal causes: (1) Being permanently corrected by vertical magnets under or above the centre of the compass; (2) By the action of a vertical soft-iron rod above or below its centre; and (3) By correctors similar to those used for quadrantal correction.

Since, however, in practice the effects of causes (1) and (2) cannot easily be separated, they, and part of (3), are treated as one and corrected by vertical magnets only, so that they are only accurately compensated for any one place, or rather dip.

Since, on change of dip causes (2) and (3) will alter, such correcting magnets will, generally, during a voyage require re-adjusting, as will be seen from an examination of Chart 4 of the Manual, apart from the indication given by the unsteadiness of the compass when steering near North or South courses.

Thus, vertical soft iron, (k), and horizontal soft iron when inclined, being magnetised only by the vertical force of the earth, will practically produce a constant force on such a voyage as that from the English Channel to the West Indies, or from the Cape of Good Hope to Torres Strait, during which the vertical forces of the earth remain much the same throughout, and therefore no re-adjustment will be required.

If, however, on a voyage from the Channel to the Cape of Good Hope, or from Sydney to Hong Kong, great changes in the power of such soft iron will take place, necessitating re-adjustment of the vertical magnets when suitable opportunities occur.

Thus, on referring to Fig. 10, we see that at the after compass on the upper deck causes (1), (2) and (3) will, in England, be acting together, while at the forward compass (1) will oppose (2) and (3), a condition of affairs which will be reversed at the Cape, so that to correct these combined errors in England, probably several vertical magnets, having red poles up, would be required to be placed under the centre of the after compass, while that forward would probably not require any, but as the voyage to the Cape progressed the magnets under the after compass would require to be gradually reduced in number, removed, or possibly reversed, if causes (2) and (3) are greater than cause (1), while magnets with blue poles up would require to be introduced in increasing numbers under the forward compass.

By measuring in either of the ways described on page 87, the vertical force acting at a compass when the ship is upright, in two different and widely separated dips, the part of such force due to permanent magnetism (R) could be separated from that caused by vertical soft iron, (*k*), in exactly a similar way to that by which the two components of co-efficient B are separated (page 35).

There is, however, at present, no practical object gained by doing this; as there is no suitable corrector we could separately apply for cause (2), since, though theoretically, this could be done by lengthening and raising the Flinder's bar, thus introducing a vertical upwards force (in the northern hemisphere), such procedure would disturb the correction of the semi-circular deviation, and be otherwise very inconvenient and unpractical.

Cause (3), as we shall see, is largely corrected by the quadrantal correctors.

From the foregoing, we see that while cause (1) might produce either + or − heeling error at a particular compass, which will keep the same sign in either hemisphere, causes (2) and (3) may both be expected at a compass on the upper deck to cause + heeling error in the northern, and − in the southern hemisphere; hence the generally observed fact—to which, of course, there are exceptions, arising from cause (1) being both powerful and negative—that compasses so placed show + heeling error when north of the magnetic equator, and − error when south of it. This may also account for some recorded observations of supposed magnetic attraction of land in the northern hemisphere when passing near it, and heeling while on northerly or southerly courses, the north point of the compass being apparently drawn in towards the land, but really attracted to the high side of the ship.

Occasionally for scientific purposes, and to test the accuracy of existing modes of correction as well as the formulæ on which these are based, ships both uncorrected and corrected are heeled over both ways and swung in these positions, the deviations then observed being compared with those found when the vessel is upright; but as this is a lengthy, expensive, and, as experience shows, unnecessary operation, in all ordinary cases the correction for heeling error is always made when the ship is upright, or in other words, by calculation instead of experimentally.

Of the three sources of error we wish to compensate, that of a large part of cause (3) is perhaps the most simple.

This correction is practically effected at the same time and by the same means as that employed for the correction of quadrantal error.

Thus, in Fig. 57, we see that as the ship heels and the upper parts of horizontal soft iron (represented by rod *e*), become, in the northern hemisphere, endued with blue magnetism, the attractive effect which this has on the north point of the compass tends to be neutralised by both the repelling action of the red magnetism of the under part of one sphere and the attractive influence of the upper part of the other, similar but reversed effects occurring in the southern hemisphere. In other words, the spheres by themselves, or mounted we will suppose in a wooden ship, will cause negative heeling error in the northern, and positive error in the southern hemisphere, and thus can be utilised—besides their quadrantal effect—in partially correcting the similar but opposite errors in an iron ship.

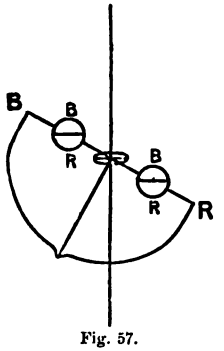


Fig. 57.

The amount of beneficial effect of this kind produced by the spheres can be calculated from the formula:—

Correction of heeling error in minutes = 2 tan dip × quadrantal error in degrees,

so that in the English Channel, where tan dip is about 2·6, the spheres will correct 5′ of heeling error for each degree of quadrantal deviation compensated.

It will be noticed that the *whole* of rod e is effective in producing this part of the heeling error, but that it is, as a rule, the *excess* of rod e over rod a which causes quadrantal error (D), and also causes the part of the heeling error adjusted by the spheres.

The correction of causes (1) and (2) of the heeling error is, perhaps, best understood by supposing at first we are dealing with an iron ship having no horizontal soft iron, so that the mean directive force acting on the needle is the same as on shore (or technically, $\chi = 1$); in this case the correction would be based on the idea of making the dip on board equal to that on shore on every point after completely correcting the semicircular error, since when we have effected this we must obviously have counteracted any vertical forces (R) caused by the ship alone, and due to permanent magnetism. Thus, if we had a freely suspended magnet, such as one hung by a fine thread attached to its centre of gravity, this, on shore, would come to rest in the magnetic meridian with (in London) its north end pointing 67° below the horizontal plane.

If this magnet were similarly suspended on board in the place of the compass, it would, in the case we are considering, again come to rest in the magnetic meridian, but would dip more than 67° if the compass were over vertical downward force, or less if over vertical upward force, but by placing vertical magnets under the centre of the compass with either red poles up in the first case, or blue poles up in the second, we could make the dip 67° on board and thus correct the heeling error.

If we now suppose that the compass, as is usually the case, is not only affected by hard iron but by horizontal soft iron, and that this has been corrected—as far as deviation when upright is concerned—by spheres, there remains to be considered the action of equal parts of rods *a* and *e*, or rather, such part of *e* as remains acting.

As these reduce the horizontal force, our dipping needle would show greater dip before the vertical magnet is introduced than in the first case.

In other words, although the reduction of horizontal force will not affect the *amount of* vertical force on board, it will cause it to produce a greater *effect*, shown by the increased dip; but if we again, by vertical magnets under the compass, make the dip on board equal to what it would be on shore if the earth's horizontal force *there* were similarly reduced, we shall remove the heeling effect of vertical force on board as modified by the spheres, still leaving in the action of that part of *e* which is unaffected by quadrantal correction.

When the quadrantal has not been corrected we have to allow for the heeling action of the *whole* of rod *e*, which action, before heeling, would be manifested by the dipping needle showing on an average more dip than in the last case.

This mode of procedure with a dipping needle freely suspended would, in such cases as we have taken, be *practically* impossible to carry out, as magnets suspended by threads are very difficult to manipulate on board, and moreover, since in practice, for other reasons the semicircular deviation is not corrected before the heeling error is adjusted, the dip observed on board, when the needle comes to rest, would differ from that it would have in the magnetic meridian.

Since, however, the dip is dependent on the proportion between the horizontal and vertical forces acting on the needle, we can attain our object, practically, by suitably regulating this proportion.

As the horizontal force on board cannot practically be altered, any desired ratio between these forces is always attained by placing vertical magnets under the compass, by which means the vertical force can be varied by any amount or in any way desired.

The proper distance at which to place these magnets is most accurately determined by comparisons between the vertical forces on board and on shore, and not by the "dips" produced by their action; such forces are compared by the vibrations of a vertical magnetic needle on board and on shore; the forces in the two cases are thus compared in exactly the same way, as by similar comparisons of the vibrations of a horizontal needle the horizontal forces were compared *(page 70)*.

A dipping needle on shore supported on pivots and lying with its poles in the plane of the magnetic meridian, comes to rest with its axis in the line of dip, but if turned round out of the plane of the magnetic meridian the dip will apparently increase, and if lying East and West magnetic the needle will hang vertically, being then only acted on by the vertical force of the earth, the mode of support by pivots then preventing any horizontal action.

Suppose that in this position on shore such a needle makes 10 vibrations in 12 seconds (T), and when similarly mounted on board in, as nearly as possible, the plane of the compass needles it makes 10 vibrations in 14 seconds (T_1), then:—

Vertical force on board : vertical force on shore : : $12^2 : 14^2$,
or nearly as 7 to 10,

so that if we call the earth's vertical force alone, or that on shore 1, then the similar force on board on this particular point, or that of earth and ship combined, will be ·7.

In most cases this result would be practically found with the ship's head in any direction, but at a compass placed far forward or far aft, individual values may differ *(see page 90)* though the mean would remain the same.

Such mean value of the vertical force of ship and earth combined is termed "mu" (μ), and as the needle vibrates, in this case more slowly on board than on shore, we should conclude that there was, on the whole, red magnetism under the compass, which would thrust up its north end, and therefore give negative heeling error.

This would require correction by vertical magnets, blue poles up, placed under the centre of the compass, and raised or lowered until the time of vibration of the vertical needle was quickened so that it made 10 vibrations in somewhat more time than it did on shore; if it made the vibrations at the same rate on board as on shore, it would show that we had made the vertical force on board the same as on shore, and thus for the place corrected causes (1) and (2), but the remainder of cause (3), or the vertical force, and positive heeling error, called into play on heeling by that part of the athwartships horizontal soft iron (e), which is not affected by the spheres, will require to be counteracted in any one dip by raising or lowering the vertical magnet and introducing a small negative error. The distance it has to be moved depends upon the value of rod e after quadrantal correction, the downward vertical force requiring reduction in the proportion of 1 (or force on shore) to $(1 - e)$.

Should it be intended, as is sometimes the case in merchant vessels, to correct the heeling error but not the quadrantal, it must then be remembered that the whole of rod *e* is acting, and the proportion will then be as 1 to (1 + *e*). Rod (*a*) does not affect the heeling error. As in analyzing a deviation table, we do not usually find the power of the individual soft iron rods, but only that of their combined effect as co-efficients, it is more convenient to express (1 – *e*) or (1 + *e*) in terms of λ and D, so that to allow for all sources of error, the time of vibration of the vertical needle on board, (T_1), must be made equal to $\frac{T}{\sqrt{\lambda(1+D)}}$ if the quadrantal be corrected, or to $\frac{T}{\sqrt{\lambda(1-D)}}$ if it be not corrected.

Thus, in the example we have taken, if $\lambda = \cdot 8$ and $D = \cdot 15$, the time of making ten vibrations on board must be reduced from 14 seconds to 12·5 seconds.

The great increase in the amount of the changeable part of the heeling error in modern vessels of war, due in large measure to the increased amount of soft iron, represented by armour, &c., which is employed in their construction, necessitates, however, the use of a more simple means by which the navigator can periodically test the heeling error, and if necessary, re-adjust the vertical magnets, in harbour or at sea, without heeling the ship; this is effected by the use of what is known as the "Heeling Error Instrument," or in a slightly different form as Thomson's "Vertical Force Instrument." The Heeling Error Instrument is a thin cylindrical steel magnet, graduated in a scale of equal parts from its centre towards each end.

Supported at its middle point on smooth agate plates, this needle (Fig. 58), placed on shore in the magnetic meridian, would dip (in London) with its north pole 67° below the horizontal plane, but is kept in a horizontal position by a small sliding aluminium weight placed over its south or upper end, this weight, when adjusted to the proper distance from the centre, balancing the earth's vertical force which tends to pull the north pole downwards.

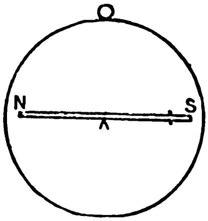


Fig. 58.

On taking the needle on board with the weight in this position, and placing the glass case containing it, by a suspended chain, so that the needle lies in the magnetic meridian and in the plane of the compass needles, its north end will incline upwards or downwards according to the difference between the magnetic forces (horizontal and vertical) on board and on shore; and at first glance it would appear that to correct the heeling error we should place vertical magnets under the compass, so as to make the needle again horizontal without any re-adjustment of the counterpoise; this, however, would be to leave out of consideration the effect of the horizontal athwartships soft iron or rod *e*.

To allow for this, before making the needle horizontal on board by the corrector magnets, the aluminium weight must be pushed *in* somewhat towards the centre, the amount required differing at different compasses, and found by multiplying the scale division at which it is set on shore by a number which is constant at each compass for all places (technically known as the "multiplier"), which at a compass corrected for quadrantal error is λ (1 + D), and for one uncorrected for such error is λ (1 − D).

As λ is always less than unity, λ (1 + D) is *generally* and λ (1 − D) *always* less than 1, so that as the horizontal needle is graduated from the centre, the aluminium weight has usually to be pushed in towards the centre.

This of course is equivalent to reducing the downwards pull under the compass, as in the case of doing the same thing by oscillations of a vertical needle.

In the southern magnetic hemisphere the counterbalancing weight will require to be placed over the north end of the needle, and similarly on board moved towards its centre.

At sea, where of course no shore observation is possible, we must calculate (by referring to chart 4 of the Manual, or No. 3 at the end of this book) what the shore reading would be if we could land alongside the ship.

Thus, suppose at some previous time the shore reading at the Cape of Good Hope had been 16, the weight being over the north end of the needle, and that, on a very smooth day, when in the South Indian Ocean—say in lat. 40° S., long. 85° E.—it is desired to recorrect the heeling error.

On referring to the above mentioned chart* (which shows curves of equal vertical force on the earth similarly to the well known Variation Chart) we find that the line of vertical force passing through the ship's position is that of − 2·75, while that passing through the Cape is − 1·6: could we therefore land abreast of the ship in order to make the needle horizontal, the counterbalancing weight (still over the north end of the needle) would have to be moved *further* from the centre than it was at the Cape, in the proportion of 2·75 to 1·6, since the vertical force is now greater than it was.

If, then, the Cape reading be multiplied by $\frac{2·75}{1·6}$ we get 27·5, the probable shore reading at the position we are in; on again multiplying this calculated shore reading by the known "constant" for the compass, we get the reading at which to set the aluminium weight before bringing the needle horizontal by raising or lowering the vertical magnets under the compass.

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*This convenient chart is constructed from a combination of the data given on those of Dip and Horizontal force, since Vert. force = Hor. force × tan dip, the Horizontal force at any place being expressed in terms of that at Greenwich considered to be 1.

The effects of some smaller causes of heeling error will now be considered.

If we compare the deviation curve of an uncorrected compass, observed in a ship when upright, with that of the same compass when the ship is heeled over either way, we find that the disturbance in the arrangement of iron relative to the compass, in the latter case, introduces (1), a semi-circular error; (2), a constant error; and (3), a quadrantal error, in addition to the similar errors existing before heeling.

Of these additional errors, (1), as we have seen, is the combined effect of vertical permanent magnetism, (R), vertical soft iron, (*k*), and vertical induction in horizontal soft iron, (*e*), and this is, fortunately, the only part we need to practically consider. Parts (2) and (3) are brought about by the unsymmetrical positions into which rods (*c*) and (*g*) are brought by heeling (*see* Fig. 22), and these almost always produce very small effects; that caused by rod (*c*) is completely corrected when Flinder's bar is applied, the error thus compensated having been already referred to (page 29); the lower end of the bar also partly neutralises the effect of vertical soft iron under the compass, or rod (*k*). The error caused by rod (*g*) requires more consideration.

Among the forces produced by the earth's induction on the horizontal soft iron of a ship is one which can be typically represented by such a rod as (*g*), Fig. 22, lying fore and aft and below the centre of a compass, if on the upper deck.

Such a rod (Fig. 59) is magnetised so that the end nearest north always has red magnetism, and that nearest south blue magnetism, anywhere on the earth and in all positions, except when lying East and West magnetic, when it is not magnetised at all; so that, while a compass, (2), far from either bow or stern is unaffected by it, one placed well forwards, (1), will experience from this an upwards thrust (and therefore negative heeling error) with the ship's head on northerly courses, being most affected at North

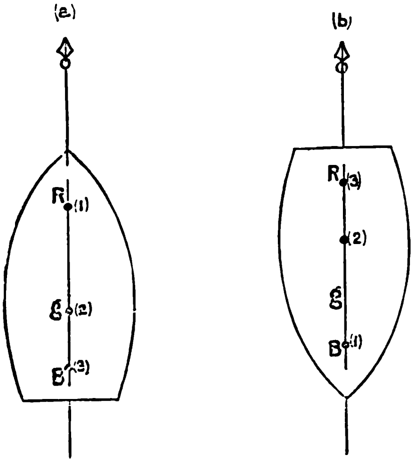

Fig. 59.

magnetic, and an equal downwards pull (and therefore positive heeling error) on southerly courses, being most affected at South magnetic, while exactly opposite effects will be produced at a compass (3) near the stern, so that from this cause the heeling error is at a maximum at north or south magnetic and is nothing at east or west magnetic, retaining the same value on the same point everywhere in the world for a similar reason to that causing quadrantal error to be everywhere the same.

As this cause will equally augment and decrease the vertical force on board the ship arising from other causes, (μ), in opposite magnetic directions of her head, if the *total* vertical force is measured with the ship's head swung in a tideway, on practically opposite points, from such observations the two causes can be separated (*see page* 73 *of* Manual) with the object of leaving in the part of the heeling error due to (g) when adjusting by vertical magnets, as no convenient corrector can be applied to it.

It is more simple, however, to make such magnet correction with the ship's head East or West magnetic, as (g) is not then acting. Theoretically, the value of (g) could be found by observing the changes introduced into A and E by heeling the ship (*see page* 56), but an inspection of Table 6 of the Manual shows that, practically, it generally has only a small value.

The very large heeling co-efficients (3° to 4°) found in some modern vessels of war necessitate making provision for a considerable number of vertical magnets, so that the case containing them is capable of holding seven of 14 inches length, placed parallel and close together, their united axis being immediately under the centre of the card.

The desired effect is usually obtained by using a smaller number and keeping the case fixed as low down as possible; if, however, to obtain the power required the case must be raised, the upper poles of the vertical magnets should not be brought within 30 inches of the compass needles, unless special precautions are used to obviate an error then brought into play by the mode of suspension of the Thomson compass (*see* Manual *page* 87).

EXAMPLES.

1. Describe the chief causes of heeling error, and illustrate their effects by figures adapted to both the northern and southern hemisphere.

2. A battleship, with the standard compass placed over a conning tower, heeled 3° steadily to port, when 9° W. deviation due to heeling error were observed. Ship's head South by compass.

Describe how this may be corrected:

(*a*) Whilst the ship remained heeling over;

(*b*) When the ship was trimmed upright and the compass showed no deviation.

3. In the instructions for using the heeling error instrument, it is directed that the magnets are to be lowered 1½ inches after the balanced needle is made horizontal by them on board. Give reasons for this instruction.

4. When correcting the heeling error the ship's head should be placed nearly East or West. Why not on North or South?

5. Before correcting the heeling error the quadrantal correctors and Flinder's bar should be accurately placed. Why should this be ?

LECTURE VIII.

Adjustment of all Errors by (1) Bearings (2) Deflector.

Having in previous lectures examined in detail the various forces which cause the deviation of a compass in an iron ship, we will now finally consider them as we find them in practice, that is, all acting together, and this will be best done by supposing we have to adjust a compass at which all five co-efficients are acting.

Before going on board we should carefully ascertain, in a place free from local magnetic disturbance, the rates of oscillation of the horizontal and vertical needles which will be required for the correction of the heeling error.

Having adjusted the counterpoise over the south end of the short horizontal needle so that it hangs horizontally, (*see page* 88), and after carefully levelling the small dip circle and turned it round its axis so that the needle is vertical (*see page* 87), each, lying in the plane of the magnetic meridian, would be drawn about 20° on one side of its position of rest and then allowed to swing freely. From the mean of several sets of observations suppose we find that the time (T) of making ten swings (to *and* fro) is for the horizontal needle 18·5 seconds, and for the vertical 12·2 seconds (T).

On going on board, the compass direction of the ship's head is noted (N. 40° E.), and, if possible, the deviation on that point observed (9° E.), though this might, perhaps, have to be deferred until the ship is swung.

The compass card being removed, the horizontal needle is mounted on the same pivot as used on shore, on a block of wood so as to be exactly in the plane of the compass *needles*, when, on vibrating it as on shore, we find the mean of several sets of observations gives 23·2 seconds as the time (T^1) of making ten swings.

The dip circle is now mounted in the binnacle on a wooden support so that its centre is in the plane of the compass needles, and, after levelling, it is turned until the needle hangs vertically, when, on taking the mean of several sets, we find the time of making ten vibrations on board is 14·4 seconds.

The compass card is then replaced, and at slack water the ship swung slowly on as near as may be every alternate point; when the tide having turned and the ship swung with her head S. 30° W. deviation 10° E., the observations with the dip circle are repeated, the time of making ten vibrations being now 13 seconds (T_1).

We next draw the deviation curve from the observations on exact or non-exact points as the case may be, and take off the deviations on the eight principal compass points as on the following table:—

North	+ 10°	South	− 14°
N.E.	+ $8\frac{3}{4}$°	S.W.	+ $21\frac{1}{2}$°
East	− 15°	West	+ $27\frac{1}{4}$°
S.E.	− $34\frac{1}{2}$°	N.W.	+ 12°

On substituting these values in the equations given on page 162, or on page 62 of the Manual, we find the exact co-efficients as follows:—A = + ·034; B = − ·414; C = + ·165; D = + ·226; E = − ·072.

In using the formula on page 162, we must remember that a symbol such as δ_4 means deviation at N.E. and δ_{28} deviation at N.W., the direction of the ship's head being counted in points continuously from north through east, south and west, while δ_4 is the abbreviation for nat. sine 4 points or ·707.

As the deviations are less than 90°, both the sines and cosines of those that are easterly will be plus (+), while those westerly will have the cosines plus (+) and the sines minus (—).

A rough guide to the accuracy of the calculation will be afforded by the approximate co-efficients, with the signs of which those that are exact ought to agree, and also, roughly speaking, to equal their natural sines.

Thus, by inspection, from the deviation table we see that the approximate B = − 21°, whose natural sine = − ·358, which is sufficiently near to the value of the exact B (— ·414) to show no mistake has been made in the working.

Having thus found the exact co-efficients we proceed to calculate λ, or the mean pointing power of the compass, by substituting our observed values in the equation :—

$$\lambda = \frac{T^2}{T_1{}^2} \times \frac{\text{cos. dev.}}{1 + B \text{ cos. Co.} - C \text{ sin Co.} + D \text{ sin. 2 Co.} - E \text{ cos. 2 Co.}}$$

where T = 18·5; T_1 = 23·2; dev. = + 9°; and Co. (which means magnetic course) = N. 49° E.; from this we find λ = ·750.

The course is counted through North by east and south to 360°, so that from north to east, inclusive, both sines and cosines are +; from east to south, inclusive, sines are + and cosines −;

from south to west, inclusive, both sines and cosines are $-$; and from west to north sines are $+$ and cosines $-$.

In most cases E is too small to be worth considering in this calculation.

We next proceed to find the value of μ, or the mean vertical force on board.

The object of making originally *two* observations of vertical force was to ascertain if any part of such force was caused by the action of rod g (*page* 91), since this producing opposite effects on points 180° apart will alternately augment and decrease μ, or the mean vertical force.

If the tide admitted of the two observations with the vertical needle being made on points *exactly* 180° apart, then, as the value of μ would be *equally* decreased and increased by g, the mean of the observations made with the vertical needle, as compared with those on shore, would at once give μ, but if the points are not exactly opposite, the values of μ and g must be separated as shown on page 73 of the Manual.

In this case as the directions of the ship's head are so nearly opposite, we take the mean of 14·4 sec. and 13 sec. (13·7) and find $\mu = \frac{T^2}{T_1{}^2} = \frac{12{\cdot}2^2}{13{\cdot}7^2} = {\cdot}802$. Unless the compass is near one end of the ship, g is so small that it can be disregarded.

With this value of μ we can now find the time which ten swings of the vertical needle *ought* to make when our future correction for heeling error is effected.

If circumstances will admit of placing the ship's head East or West magnetic at the time of such correction, since g is not then acting, the desired time is found from the formula,

$$T_1 = \frac{T}{\sqrt{\lambda(1 + D)}}$$

which in the present case gives $T_1 = 12{\cdot}7$ seconds.

If, however, the ship cannot be turned to East or West magnetic, but is to be adjusted while still lying with her head S. 30° W., some allowance must be made for such part of g as is then acting, and, therefore, T_1 is found from the more complicated equation on page 178 of the Manual.

These formulæ are those used in the usual case where correction for quadrantal error precedes that for heeling error.

Our next step is to calculate the value of the total quadrantal deviation in degrees and correct it.

The values of the exact D and E being $+{\cdot}226$ and $-{\cdot}072$, the angles of which then are the natural sines, *viz.*, $+13°$ and $-4°$ will be very nearly those of the approximate, D and E, or the deviations which they will produce.

Hence, we see that the total quadrantal, or $\sqrt{D^2 + E^2}$, is $13\frac{3}{4}°$, which, on reference to Table 4 of the Manual, can be corrected by a pair of 15-inch spheres set out half-an-inch.

As $\frac{E}{D} = \frac{4}{13} = \cdot 307$, the angle of which, this is the natural tangent (17°), will be twice that through which the line of spheres must be rotated, that angle being measured from the athwartships line with the azimuth circle.

As E is $-$, the starboard sphere is moved forward through an angle of 8½°, and a pair of 15-inch spheres put on each at a distance of half-an-inch from being close in to the compass.

The quadrantal error is usually corrected *before* the heeling error, mainly because doing so tends greatly to steady the compass, especially if it has a large value, and also corrects a part of the heeling error.

Flinder's bar is next put in place, its length and position being generally determined from Table 5 of the Manual, or by estimation. Thus, if our ship is of a similar type to *H.M.S. Grafton,* we should see, that of the exact co-efficient B, whose value ($-\cdot 414$) we have calculated, $-\cdot 04$ is probably due to vertical soft iron, (c), and therefore will require 10·8 inches of Flinder's bar forward of the compass, such length (or the nearest we can make up to it) being placed in the brass case on top of 13 inches of the wooden chocks supplied for this purpose.

Flinder's bar, or rather the action of its lower pole, diminishes the effect of k, or the vertical soft iron under the compass, and therefore is placed in position before correcting the heeling error.

We now, in order to correct the heeling error, remove the compass card, level and mount the dipping needle, turned with its axis north and south, so that it hangs vertically, exactly as at first, and keeping the underneath case at the bottom of its receptacle, introduce vertical magnets with blue pole up, until we find the time of ten vibrations of the needle are made in 12·7 seconds.

All errors possible to deal with are now corrected, except (1) that which is constant, (A); (2) that caused by rod g, if existent; and (3) that caused by permanent magnetism (C and the remaining part of B).

Of these, (1) is never corrected at a standard compass, but at a binnacle compass used only for steering purposes—the lubber line would be repainted 2° to starboard of its original position; (2) is also a small error for which we have no corrector.

The correction of the errors from permanent magnetism will be made, experimentally, at the next slack water, by putting the ship's head on the nearest convenient cardinal point—say East magnetic—and introducing a sufficient number of fore and aft magnets, with blue poles forward to correct the remainder of B, using such magnets as far as possible in pairs, and filling up the lower holes first, or, if they are moved up and down by a rack, keeping them as low down as possible.

The ship will then be turned to the most convenient adjacent cardinal point—say North magnetic—and C corrected by athwartships magnets with red poles to starboard.

Of course, in both these cases the whole of the deviation is not corrected, but 2°, or the amount of A, is left in, and, on now turning the ship's head to West and South magnetic, this ought to be the only deviation remaining.

If, intending to correct the heeling error by using the horizontal needle (heeling error instrument), a preliminary observation is made on shore with the needle approximately in the magnetic meridian, and the counterpoise moved until it is horizontal when the divisions from the centre at which the counterpoise stands is read off on the needle—say 29 divisions. From the results of swinging, the value of λ (1 + D) is calculated, − in this case 750 (1 + ·226) = ·92.

The shore reading of 29 is now multiplied by this constant, and the counterpoise pushed in to this reading (26·7) when the needle mounted on board in the plane of the compass needles, and lying approximately in the magnetic meridian, is brought into a horizontal position by the vertical magnets under it.

In correcting heeling error, by either method, it is usual, but not essential, to do so after the quadrantal error has been compensated; if making the adjustment before correcting quadrantal, the same formulæ are used, but λ (1 − D) is substituted for λ (1 + D).

The foregoing represents what is necessary to be done to correct a compass under the peculiar circumstances it is in on board a vessel of war. In more ordinary cases the errors may be reduced to comparatively small amounts, without so much calculation, by experimentally correcting the semi-circular deviation on two adjacent cardinal points by magnets and Flinder's bar, and then putting on spheres with the ship's head turned to a quadrantal point; the heeling error would be approximately corrected afterwards by using the horizontal needle, assuming values for λ and D.

Under all circumstances, after completing compensation, the ship is again swung, and the small remaining errors tabulated.

As an illustration of the mode of procedure in ordinary cases, where no A nor E exists, of correcting a compass by the "Deflector" method, we give a translation of the practical rules (as approved by Lord Kelvin) given in the French Manual of Deviations.

With the ship's head North or South, by compass, the fore and aft magnets are used.

With the ship's head East or West, by compass, the 'thwart-*ship* magnets are used.

When the reading of the deflector is to be increased, if there are no magnets in position, place them with their poles set in the opposite direction to those of the deflector when it is in the position which causes normal deflection at the time.

If there are magnets in position, bring them nearer, if their poles are set in the opposite direction to those of the deflector. Remove them farther off if their poles are set similarly to those of the deflector.

When the reading is to be diminished, if their are no magnets in position, place them with their poles set in the same direction as those of the deflector.

If magnets are in position, bring them nearer, if their poles are similarly set to those of the deflector. Remove them farther off, on the contrary, if their poles are set in the opposite direction to those of the deflector.

1.—*Ship's head North by compass.*—Make the observation for normal deflection, suppose the corresponding reading to be 20·2. Return the card with the help of the deflector to its original position; then take the latter away, and satisfy yourself that the ship's head has remained within 4° or 5° of the same direction during the time of observation.

2.—*Ship's head East by compass.*—Make the observation for normal deflection. Let the reading corresponding be 8·4. Return the card to its original position with the help of the deflector, and verify that the ship's head has not changed.

3.—*Ship's head South by compass.*—Make the observation for normal deflection. Let the reading be 14·8. Return the card to its original position, &c., as before.

The reading found with the ship's head north was 20·2
The reading found with the ship's head south was 14·8

The sum of the two readings is 35
And the Mean 17·5

By means of the screw, set the index at 17·5. Place the deflector on the compass bowl with the pointer over the north. Now, keeping the ship as exactly as possible in the same direction by means of the auxiliary compass, place the fore and aft corrector magnets in such a way as to obtain the normal deflection with the reading 17·5.

The deflector reading has been increased, and there are no magnets in position, therefore they must be placed with their poles in the opposite direction to those of the deflector. The magnets are brought nearer until the normal deflection is obtained. They are then fixed in the position they occupy.